SEDIMENT RESPONSE TO LARGE-SCALE ENVIRONMENTAL CHANGE: THE UPPER MISSISSIPPI RIVER, 1943-1996

By

RICHARD P. R. PANNELL

A thesis submitted in partial fulfillment of

the requirements for the degree of

MASTER OF SCIENCE

(GEOGRAPHY)

at the

UNIVERSITY OF WISCONSIN-MADISON

1999

19990528 001

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ABSTRACT

Knowledge about sediment yields is important in developing management strategies for fluvial systems. The effect of sediment must be considered in the design of river structures and in determining water quality for biotic systems. Changes in sediment transport regimes are difficult to understand or predict due to the complexity of factors that influence sediment flux in fluvial systems. Relationships about sediment source, sinks and transport have long been studied and many of these relationships have been quantitatively and qualitatively defined. However, due to the scarcity of long-term sediment records it is often difficult to test these relationships. This study examines one of these long-term suspended sediment records for the Mississippi River at East Dubuque, Illinois from 1943 to 1996.

Daily suspended sediment concentrations from the United States Army Corps of Engineers station at East Dubuque were analyzed for the spring and summer months (March-August). Sediment concentrations were analyzed in terms of average concentration during different hydrologic events at the large basin scale. These events included the spring snowmelt runoff (low and high magnitude) and different intensity storm runoff (low, moderate and high). Additionally, peak sediment concentrations during storm runoff were also analyzed.

The general trend for all of these analyses suggests a significant decrease in sediment concentrations from the 1940s to the 1990s. The strongest trends are found in high magnitude snowmelt runoff and in high and moderate magnitude storm runoff. Peak concentrations in storm runoff have decreased from about 1000 ppm in the 1940s to about

200 ppm in the 1990s. Average concentrations have likewise decreased from about 200 ppm in the 1940s to 100 ppm in the 1990s. Changes in land management practices are identified as being the primary environmental factor influencing sediment concentrations. An analysis of storm frequencies over the period from 1949-1996 suggests that changes in climate over the record have had minimal impact on the long-term temporal trend of suspended sediment concentration. However, an analysis of discharge variability demonstrates that sediment concentrations are being influenced by the annual and decadal variability of climate in terms of precipitation.

INTRODUCTION

The purpose of this study is to analyze the response of suspended sediment concentrations in the Upper Mississippi River to changing environmental conditions over a period of 54 years. Understanding the role of suspended sediment in an alluvial river is important in developing any long-term water resources management strategy. Since 1940, the Corps of Engineers in conjunction with the U.S. Geological Survey has conducted suspended sediment sampling in the Upper Mississippi River Basin. Initially, the Corps' main interest was the effect of sediment loads on the design and operation of river projects (Mack, 1970). The determination of sediment yields and the forecasting of future conditions is a necessary step in developing design criteria for reservoirs, flood protection channels and navigation projects (U. S. Corps of Engineers, 1989). By the 1970s, federal agencies began recognizing the importance of sediment loads and related problems in water and land resources management (Mack, 1970; U.M.R.C.B.S., 1970). More recently, studies have focused on water quality issues such as contaminant transport and aquatic habitat (Bhowmik, 1996; Meade, 1995; McHenry *et al.*, 1984; Nielson *et al.*, 1984). Sediment studies have been an integral part in the design and maintenance of construction projects and continue to be of essential importance in evaluating the environmental quality of the river. The Corps' sediment sampling program, initiated almost 60 years ago, provides some of the few long, continuous suspended sediment records available.

The environmental history of this period includes dramatic changes in land use and land management as well as fluctuations in climate on seasonal, annual and decadal

timescales. Since the relationship between discharge and sediment concentration is largely determined by land use and climate, changes in these factors result in changes in the sediment transport regime. Understanding changes in sediment transport is difficult because the historical record of sediment data is sparse. Few sediment sampling stations exist in the United States and most of them have relatively short records.

The sediment record at East Dubuque, Illinois is the product of one of these rare, long-term monitoring stations. Originally, the Corps established this station and others like it with the limited purpose of providing sediment information to calculate monthly and annual sediment yields to use in conjunction with design criteria. The usefulness of the data has expanded to a variety of other areas especially in terms of water quality and management. Despite this expanded role of sediment study, few efforts have been made to examine temporal trends of sediment transport, especially at the large basin scale. Part of the difficulty in such an endeavor is that changes occur in the administrative system over the life of program. This is particularly relevant to the East Dubuque record. Record keeping changed in 1967 from hard copy to electronic procedures. While this made it easier to examine records and calculate monthly and annual sediment yields, it disrupted the continuity of the data. Because of limited budgets and financial priorities, this is true for other Corps records for the Mississippi River, and for other federal agencies as well. This study seeks to put together one of these "split" records and analyze it in its entirety.

The response of sediment transport to changes and variations in the environment can be determined by analyzing a long, continuous record like the one at East Dubuque. This study explores the response of sediment concentration to specific climatic events such as

snowmelt and storm floods over this long record. Additionally, it should improve our understanding of the sediment transport relationship at the large basin scale. The information this analysis provides about sediment trends of a large basin over a long record is important for understanding sediment transport relationships. The usefulness of such an understanding can be applied to a variety of engineering and environmental applications. The prediction of sediment loads continues to be an important step for the Corps of Engineers in its construction projects throughout the country. The environmental impact of sediment on water quality and water ecosystems is increasingly important for an expanding population. Changes in the water quality of the Mississippi River serve as a "report card" for federal agencies involved in its management (Meade, 1995).

SEDIMENT TRANSPORT

Sediment transport is a function of many spatial and temporal parameters. These include a variety of climatic, physiographic and land use factors that directly and indirectly affect the ability of soil to be eroded, transported, deposited and re-mobilized. The variability of these parameters increases with the size of the study area and the time frame over which it is examined. This makes the prediction of sediment flux at a particular location difficult at best. Hydrologic variables that affect sediment yield are interrelated and the influence of an individual parameter under a specific condition is hard to determine (Piest and Miller, 1975). These difficulties make the use of empirical data critical in developing and validating sediment transport relationships.

In general, sediment concentration varies directly with water discharge. Sediment discharge is the product of these two variables and thus sediment discharge is a power function of water discharge (Meade, 1982). At low flows, there is very little sediment generated, but as the discharge increases, the sediment load increases geometrically (Piest and Miller, 1975; Knox *et al.*, 1975). For low intensity runoff events, sediment concentration in a stream is relatively low at the beginning of the runoff period and increases slowly as the runoff increases. It then reaches a peak and begins to taper off. For intense storm events, concentration is much higher at the beginning and increases much more rapidly. The maximum concentration is reached prior to the discharge maximum (Piest and Miller, 1975). This is especially true when a storm is preceded by long periods of dry weather during which

easily erodible and transportable material accumulates (Piest *et al.*, 1975; Piest and Miller, 1975; Richards, 1993).

CLIMATE

The effect of climate on sediment transport is extremely important. Temperature and rainfall characteristics determine the hydrologic regime for a watershed. Regular temperature changes usher in seasonal variations including the accumulation of snowpack in winter and its delivery as runoff into the streams and rivers during spring. Temperature also regulates the evaporation rate, thereby influencing the hydrologic cycle. The impact of rainfall on soil initiates the process of sediment production, and surface runoff transports the sediment through the drainage network. The magnitude and frequency of rainfall events are central in the transport of sediment.

Storm magnitude has several effects on sediment transport. The intensity of a storm determines the amount of soil that is eroded from a particular area. Large, intense storms have greater erosive potential than small, scattered rainfall. The magnitude of the storm also relates directly to the runoff hydrograph and thus affects the rate at which sediment is transported through the system and the distance that it can be carried. The flood wave has the ability to remobilize sediment stored on valley floors, mid-channel bars and along the riverbed, generating and transporting additional material. Over time, long intense storms can deplete the availability of sediment in the system, affecting sediment loads of future events. Finally, storm magnitude has an effect on the moisture conditions for a particular basin, influencing the erosiveness of the next storm event.

Storm frequency and the timing of storm events during the year are also significant in terms of generating and transporting sediment. An increase in the number of storms generally increases the overall sediment that is transported. However, a storm that occurs shortly after the previous one will have reduced sediment concentrations, because the easily erodible sediment does not have time to accumulate. Thus, there is a recovery period required between similar storm events to generate similar sediment loads. Additionally, sediment transport is further reduced by antecedent moisture conditions imposed by the preceding storm. The timing of storms throughout the year is also significant in terms of the annual vegetation cycle. Soils that have experienced periods of high exposure, particularly in the spring, are more susceptible to the erosive forces of rainfall than they are in the summer and early fall when vegetative growth is at a peak. Likewise, the infiltration of surface runoff is lower during times of sparse vegetation. This means that more runoff and more sediment production should occur in the spring than in the late summer for a similar event.

Climate also affects the type of runoff encountered. The runoff from snowmelt is distinctly different in nature than the runoff from a storm event. Coupled with these differing runoff regimes are different sediment production regimes. Figure 1 compares hypothetical hydrographs for storm runoff and snowmelt runoff. The storm event is higher in magnitude but shorter in duration than the snowmelt event. The peak sediment concentration during storm runoff typically arrives ahead of the peak discharge. The energy of rainfall impact mobilizes sediment at the beginning of the event, but over time sediment availability decreases. In contrast, the sediment peak of snowmelt runoff may not arrive

Storm Runoff   Snowmelt Runoff
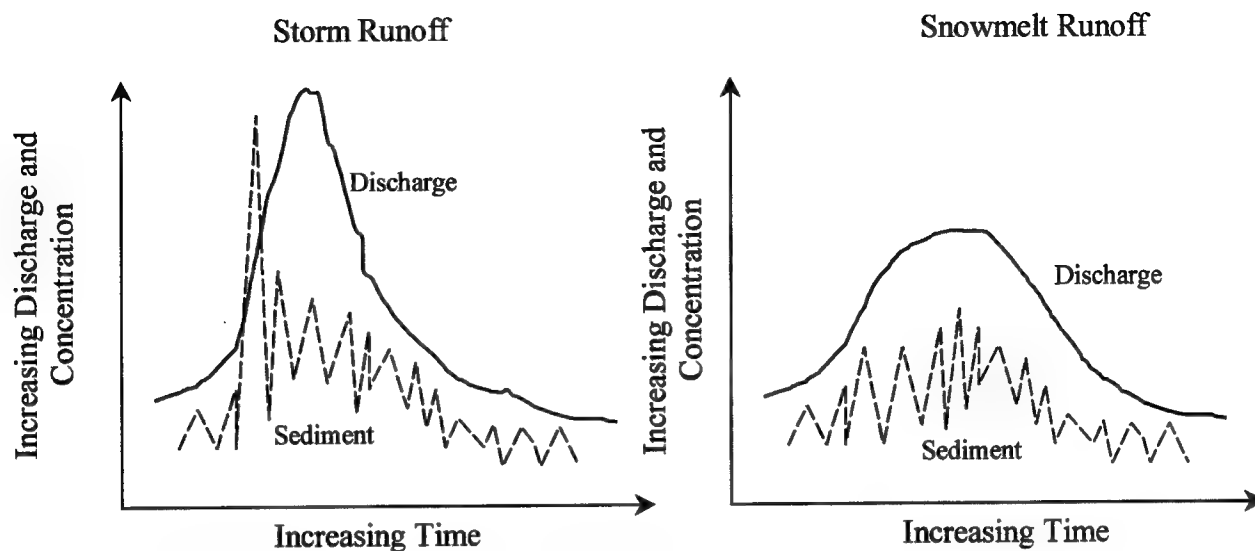
Figure 1. Storm discharge vs. snowmelt discharge

until after the discharge peak. In this case, the sediment peak is generated by the erosive force of the flood wave rather than by the energy of rainfall.

Several studies have examined sediment transport relationships in North America. In the Upper Mississippi Valley, a study of sediment yields in 20 drainage basins analyzed the average number of days during which one or more percent of the total annual suspended sediment yield was transported. An average of eight to ten high yield days accounted for over 90% of the total load for small basins (Knox *et al.*, 1975). In the Black Earth Creek watershed in southern Wisconsin, a three day period of high water discharge accounted for 52% of the total annual suspended sediment load (U.M.R.C.B.S., 1970). Dimissie (1996) examined sediment loads for flood events in Illinois. This study found that the annual flood transported on average 20% and 23% of the annual sediment load for large and small rivers

respectively. Additionally, the two highest annual floods transported from 32% to 43% of the annual sediment. These analyses indicate that a large percentage of sediment is transported in a relatively small percentage of time in the year.

In the Upper Mississippi Valley, Knox *et al.* (1975) showed that significant annual and decadal variations exist in the functional relationship between sediment and discharge. They found mean sediment yields to be significantly higher in wet years than in dry years. This held true except in large basins during the spring, which were primarily influenced by antecedent winter conditions as a result of snowmelt. This study also established that the availability of sediment to be transported depended significantly on the antecedent environmental factors affecting the watershed (Knox *et al.*, 1975).

A similar study by Knox *et al.* (1981) on the Upper Black Earth Creek Valley from 1954 to 1965 analyzed the relative importance of climate variation and land use changes. An 18% increase in cultivated land occurred over this period, suggesting sediment rates should have increased. However, sediment yields actually decreased by about 50%. The reason for this was attributed to the timing of storms throughout the growing season. Storms in the 1950s were occurring in the early summers when soil was exposed. In contrast, in the 1960s very few large storms occurred during the early summer period so that exposed soil was not subjected to as much erosion. This phenomenon was recognized to be applicable only under post-settlement conditions in conjunction with seasonal land use variability (Knox *et al.*, 1981).

PHYSIOGRAPHY

Physical characteristics of a basin such as topography, geology and soil are important in determining erosion and storm runoff characteristics especially at the local scale. The gradient and length of the slope in a specific area are both directly proportional to soil erosion. Long, steep slopes will generate more sediment than short gentle slopes under the same runoff conditions. The type of soil and bedrock also influence both the infiltration of water and the rate of erosion. The physical weathering characteristics of specific materials may significantly contribute to or deter erosion. Several studies have focused on high erosion rates of the Driftless Area in southwestern Wisconsin (Trimble and Lund, 1982; Knox, 1977). The relatively steep slopes in this region and highly erodible loess soil contribute to increased erodibility.

At larger spatial scales, the physical shape and patterns of a drainage network contribute in determining where sediment originates and where it is deposited either temporarily or permanently. At this scale, time-distance relationships between flood wave and sediment wave become significant. The opportunity for temporary deposition and storage of sediment increases with the size of the catchment. The specific source of sediment can no longer be distinguished as sediment fluxes occur at different times and rates across a spatially heterogeneous maze of slopes, tributaries and valley basins. At this scale, the discontinuous nature of sediment transport becomes apparent. The movement of sediment from the source, through the network to the outlet imposes temporal lags between input and output (Richards, 1993; Meade, 1982).

The distribution of sediment sources and sinks throughout the drainage basin is difficult to determine, as is its influence on downstream sediment loads. Clearly, studies have shown that the majority of historical upland eroded sediment is being stored in low order stream bottoms and valley floodplains, relatively close to source locations (Beach, 1994; Trimble and Lund, 1982; Knox, 1977, 1987). For a large basin, such as the Upper Mississippi River, the present sediment load is a function of many past erosion and remobilization events. Thus, sediment rates for a particular sampling site are more likely influenced by nearby tributaries and relatively local processes rather than by events occurring hundreds of miles upstream at the headwaters.

LAND USE & VEGETATION

The type of land use and the existing management practices also affect sediment loads. The conversion of prairies and woodlands to farmland has been shown to result in increased sediment production and surface water runoff, often resulting in severe erosion and gullying (Piest *et al.*, 1975; Brune, 1951; Knox, 1977). The reduction of natural vegetation and the alteration of soil structure through cultivation increases the erodibility of the soil while reducing its infiltration capacity (Knox, 1997). In mid-continent North America, the sediment transport relationship is tied closely with the annual crop cycle. In general, the highest sediment discharges occur in the late spring and early summer when the ground is unvegetated or plowed and most vulnerable to erosion (Piest and Miller, 1975).

The conversion of land for agricultural use greatly increases the amount of sediment available to the system. Butzer (1974) gives an historical account of anthropogenically

accelerated soil loss, describing the agriculture expansion of the Midwest in the 19th & 20th centuries as "the most flagrant example of land abuse." One study showed that for a given basin size with similar lithologies, the cultivation of crops resulted in a tenfold increase in sediment yield (Brune, 1951). A study of California watersheds attributed a 17-fold increase in sediment yield to four land use factors: conversion of forest to grassland, fires, poor logging techniques and road construction (Anderson, 1975). In the Platte River of southwestern Wisconsin, Knox (1977) attributed significant increases in erosion and flood magnitude to European settlement and conversion of prairie and forest to agriculture.

Conversely, more recent studies have shown that improved land management practices and the re-vegetation of farmland have dramatically reduced sediment yields throughout North America since the 1930s (Trimble and Lund, 1982; Kuhnle *et al.*, 1996; Miller *et al.*, 1993; Argabright *et al.*, 1996). Practices such as strip farming and contour farming reduce runoff rates by increasing hydraulic roughness, reducing slope length and promoting infiltration. Minimum tillage practices, residue maintenance and a decrease in crop row width help to protect soil from the erosive impact of rainfall. Land use changes such as the conversion of row crops to less intense agricultural use or federal programs such as the Conservation Reserve Program (CRP) promote vegetation growth and erosion control.

Studies throughout the Mississippi River Basin have documented the role of improved land use and land management on reducing erosion rates and sedimentation. In central Mississippi, a study of the Goodwin Creek watershed attributed reduced sediment concentrations to land use changes over a nine year period in the 1980s. Kuhnle *et al.* (1996) found that a 54% reduction in cultivated land reduced the concentrations of fines and sands

by 62% and 66% respectively. They attributed this to a decrease in erodible source material and a decrease in runoff energy. A study of the Drury Creek watershed in southern Illinois found that reduced rates of sediment yield coincided with a period of improved soil conservation practices and watershed re-vegetation (Miller *et al.*, 1993). Within the Upper Mississippi River, McHenry *et al.* (1984) found that sedimentation in Pool 14 of the Mississippi River had decreased from about three to four centimeters per year in the period from 1954 to 1964 to less than two centimeters per year between 1964 to 1980, presumably from improved land management practices.

STUDY AREA

The Upper Mississippi River basin north of East Dubuque, Illinois comprises 81,600 square miles, draining most of Minnesota, Wisconsin and portions of Iowa and South Dakota (Figure 2). The Upper Mississippi River owes much of its present form to the influence of the recent glacial advances of the Pleistocene. North of East Dubuque, the topography varies significantly from the upper reaches of the basin to the nearby reaches and tributaries. The headwaters and northern tributaries in central Minnesota and northern Wisconsin have a gently rolling topography as a consequence of the retreat of the last glacial advance. In contrast, the stream-dissected Paleozoic bedrock and loess hills immediately upstream of East Dubuque consist of a well-developed drainage network with steep gradients and long slope lengths. Source material for fluvial transport also differs between these two regions. The upper reaches of the basin consist of streams draining a high percentage of relatively coarse material eroded from the glacial till deposited on the landscape. The Driftless Area and topographically similar areas west of the Mississippi River provide a greater percentage of fine material as a result of the erosion of the loess mantle that covers much of the area. These fine-grained silts and clays serve as the major contributor to suspended sediments in this section of the Mississippi River. As with many large rivers, the suspended sediment accounts for over 90% of the total load that the Mississippi River supplies to the coastal margins (Jordan, 1965).
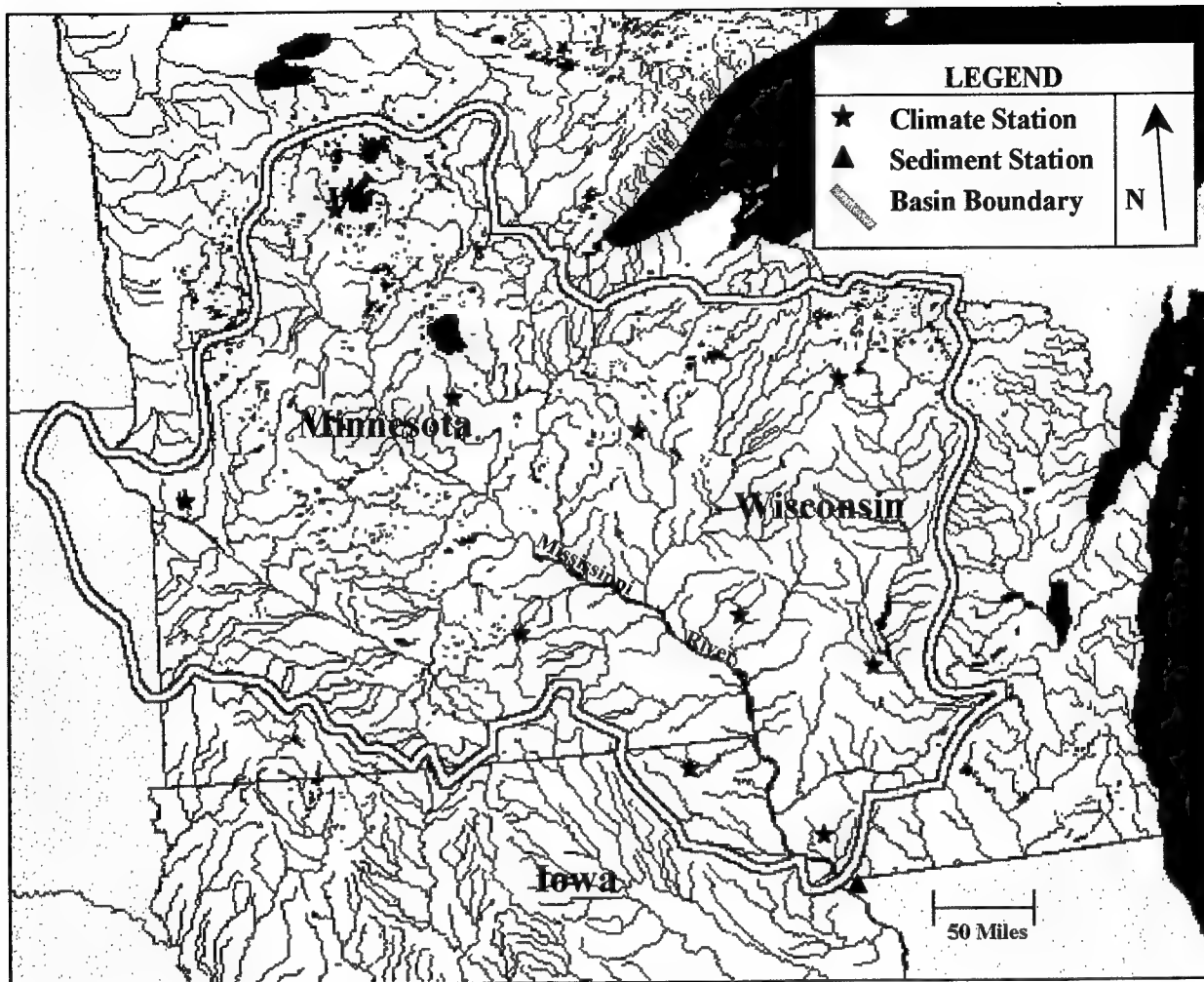
Figure 2. The Upper Mississippi River basin (source: modified from U.S. Geological Survey, National Geospatial Data Clearinghouse).

Over the last century, the Corps of Engineers has constructed a series of dams, levees

and channels in an effort to facilitate navigation and control flooding. The Upper Mississippi

River consists of a series of 26 major locks and dams to maintain a minimum river depth of

nine feet allowing barge traffic between St Louis and Minneapolis. As a result, navigation

pools have formed in conjunction with these dams and serve as settling areas for suspended sediment. Dikes and wing dams focus the main river flow into the navigation channels promoting deposition in slow moving waters outside of the channel. This has resulted in the growth and stabilization of mid-channel sandbars into permanently vegetated islands.

In terms of environmental management, the Mississippi River provides several important functions. The river is used as drinking water for 70 towns and municipalities. It provides important wetland habitat for countless birds, fish and other wildlife. The Mississippi is an important source of water, sediment and nutrients for coastal and estuarine habitats in the Gulf of Mexico. Finally, the river serves as the conveyor of chemical contaminants, much of which are absorbed and carried by suspended sediments (Meade, 1995).

Though influenced by channelization and other anthropogenic factors, Mississippi River flows are primarily controlled by the humid continental climate that characterizes this portion of the basin. Systematic cycles of spring and summer mid-latitude cyclones result in severe weather for the Midwest, significantly influencing water and sediment discharge. Spring flooding from snowmelt is often a significant factor in transporting sediment as well. Figure 3 shows average monthly precipitation rates for the drainage basin north of East Dubuque with the highest precipitation in the spring and summer months and relatively little in the winter. Also shown are average monthly discharges for the Mississippi River at Clinton, Iowa indicating April as the month of greatest discharge as a result of snowmelt combined with precipitation.
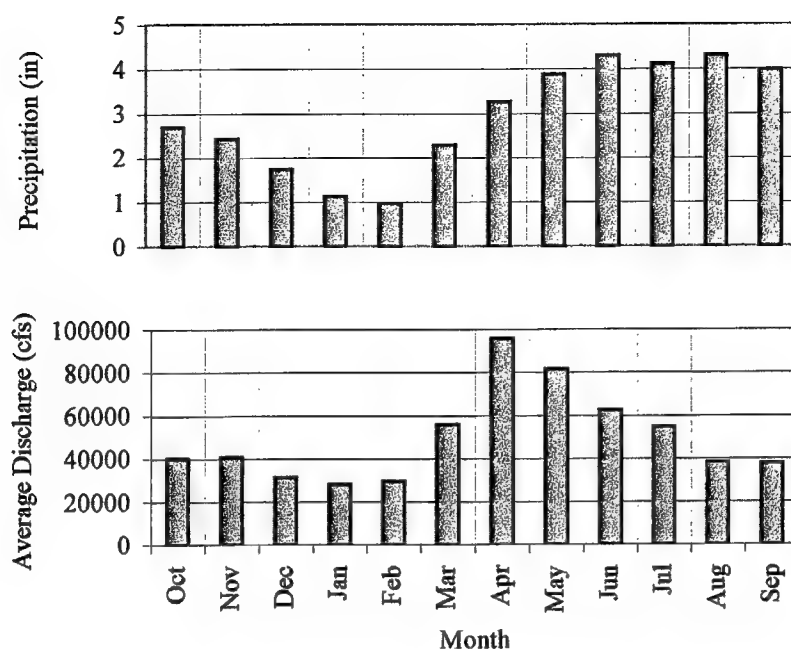
Figure 3. **Average monthly precipitation: wy1967-1993 for study area (source: U.S. Department of Commerce, *Climatological Data*, National Climatic Data Center, Asheville, NC), and average monthly discharge at Clinton, IA: wy1943-1996 (source: U.S. Geological Survey, daily discharge data).**

Since 1943, the Upper Mississippi River has experienced annual and decadal variability in precipitation. The years 1965, 1973 and 1993 experienced particularly wet springs and/or summers resulting in extreme floods for the Midwest. Table 1 shows the stage height at Dubuque, Iowa for the top ten events on record. Other periods have been relatively dry. Seasonal flows during the 1980s and the late 1950s often averaged one standard deviation or more below normal. These changing environmental conditions represent significant fluctuations that may affect the relationship between sediment concentration and discharge as previously described.

Record Highs	Date	Stage (ft)
1	04/26/1965	26.81
2	07/01/1993	23.84
3	04/24/1969	23.11
4	05/06/1975	22.78
5	04/16/1997	22.71
6	04/25/1952	22.70
6	04/22/1951	22.70
8	03/23/1973	21.85
9	04/11/1967	21.80
10	10/05/1986	21.77

Table 1. Record stages at Dubuque, Iowa (source: U.S. Corps of Engineers, Rock Island District).

Yearly fluctuations in snowmelt are also significant to the relationship between sediment concentration and stream discharge. One of the objectives of this study is to examine sediment transport under different hydrologic regimes. Therefore, it is important to look at the climate record in an effort to separate snowmelt events from precipitation events on the Mississippi River hydrograph. Figure 4 shows the late winter bi-weekly snow depth for western Wisconsin for the northwestern and central west districts, averaged over the period of 1961-1977. Typically, peak snowpack occurs in late February and begins to decrease rapidly by late March. By early April, the snow is almost gone. An approximate time period for spring snowmelt can be inferred from these data. However, attention must be given to the annual variability of these events when determining snowmelt discharge on the hydrograph. For example, the winter of 1964-65 had peak snow depths of one to two feet

during early April due to particularly cold conditions while the winter of 1967-68 had almost

no snow by the middle of March.

The influence of climate conditions in conjunction with land use determines to a great

extent the amount of sediment that is generated through erosional forces. Land management

in the upper Midwest has undergone dramatic change this century. The recognition of soil

denudation on productive and valuable farmland forced significant changes in attitudes and

practices of farming. Erosion control in Wisconsin began in earnest in 1933 with the

formation of the Civilian Conservation Corps (CCC) and their construction of roughly 900

permanent gully control structures (State Soil and Water Conservation Committee, 1963).

Coupled with Soil Conservation Service programs emphasizing land management practices

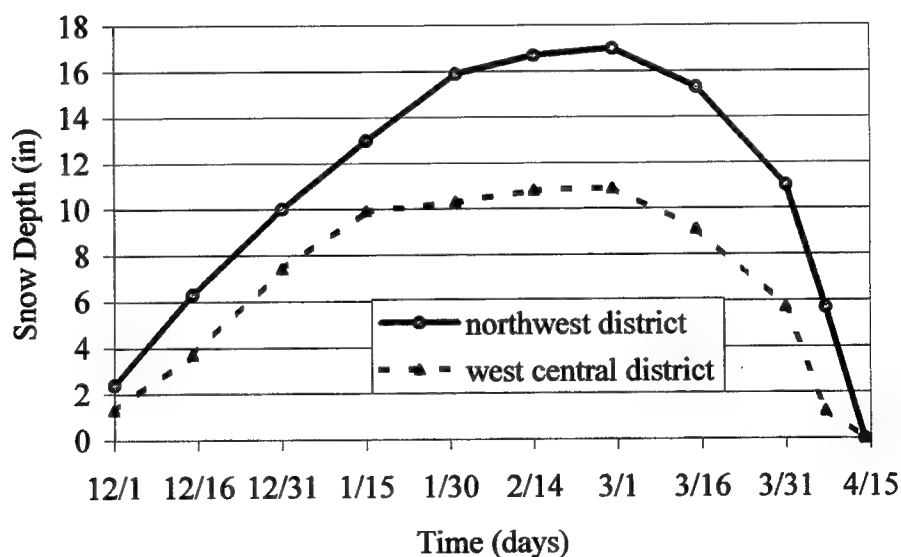such as contour farming, erosion control in the Midwest was working. Erosion rates

Figure 4. Average bi-weekly snow depths for western Wisconsin, 1961-1977 (source: Wisconsin Agricultural Reporting Service, 1978).

decreased dramatically through the 1940s after about a decade of control measures in place (Trimble and Lund, 1982). Improved land management and land use ushered the decline of erosion on the uplands, yet potential sediment sources throughout the Upper Mississippi Basin remain poised to remobilize from tributary valleys as well as the riverbed itself. The nature of this discontinuous cycle makes it essential to consider conditions in the immediate vicinity of the sampling station.

The sediment sampling site at East Dubuque is located on the Illinois Central Railroad bridge. The site is located at river mile 580 just downstream of Lock and Dam 11 (Figure 5). Nearby upstream tributaries include the Platte, Grant and Turkey Rivers, each of which is a major contributor of suspended sediment loads. Sedimentation north of the confluence of the Mississippi and Turkey Rivers has required periodic dredging maintenance by the Corps of Engineers. Historical dredging operations and dredge disposal sites are located at the mouth of the Turkey River and along its floodplain (G.R.E.A.T., 1980). The proximity of the Turkey River outlet to the thalweg is also of interest. Unlike the Platte and Grant Rivers whose outlets are over a mile from fast moving deep-water of the thalweg, the Turkey River outlet is directly adjacent to the thalweg. Another characteristic of the immediate area is the angle and length of the river reach upstream of Dam 11. Oriented northwest to southeast with considerable fetch, this section is exposed to the prevailing wind. Under sustained conditions, this wind generates sufficient subsurface turbulence to re-suspend sediment that has accumulated in Pool 11.
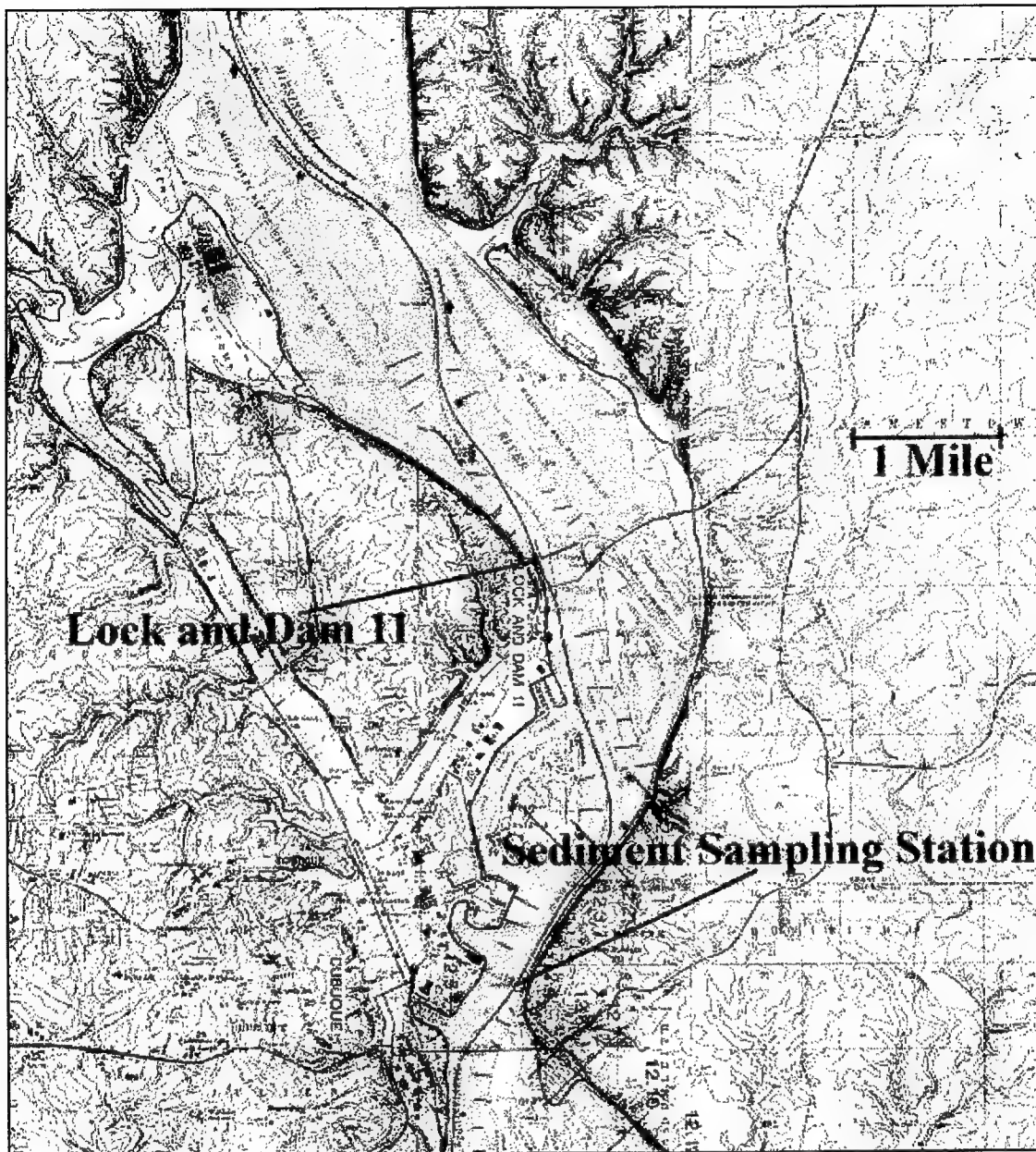
Figure 5. Location map of the East Dubuque sampling station and lock & dam 11 (source: modified from G.R.E.A.T., 1980).

DATA AND METHODOLOGY

A variety of data and methods was used to analyze the temporal relationship of sediment concentration and discharge. The data consist primarily of daily suspended sediment concentrations measured at the East Dubuque station. Additionally, the U.S.G.S. gage at Clinton, Iowa, located 68 river miles downstream, was used for daily discharge. Average monthly temperature and snow depth records for Minnesota and Wisconsin were used for determining snowmelt events. The analyses of these data focus on changing sediment concentrations over the course of the record. In several instances, data were divided into "seasons". This study refers to four specific seasons of three months each. Winter consists of December, January, and February. Spring consists of March, April and May, and so on.

DATA

Suspended sediment data for East Dubuque, Illinois were obtained from the Rock Island District of the Corps of Engineers for water years 1943 - 1996. Within this district, the Corps operates 20 suspended sediment sites, three of which are on the Mississippi River. The Corps operates two types of sediment stations. The co-op station is contracted with the U.S.G.S. and uses a rated integrated depth sampler which takes samples across the entire cross section of the river or stream. Due to expense, the Corps limits use of these to only a handful of sites deemed critical. More commonly used is the independent station. This consists of a hired observer, typically a civic-minded local, using a depth integrated sampler

such as the DU-48 or DU-78 at the deepest point of the river. Samples are then shipped to the U.S.G.S. sediment lab in Iowa City, IA where they are analyzed. Samples are taken daily, but often are not taken during winter or during periods of severe weather. On average, annual loads are computed from about 275 samples per year. In addition to sampling the sediment, the observers are required to manually measure the gage height as a back up to the electronic stream gage equipment (Beckert, 1999).

The sediment sampling station at East Dubuque is an independent station located where the Illinois Central Railroad crosses the Mississippi River. The sediment station is operated by the bridge operator who is located over the navigation channel. Typically, he conducts the sampling in the morning soon after he arrives at work. Such a situation is beneficial to both the bridge operator and the Corps since the sediment sampling site is co-located with his job site, making the data collection perhaps more reliable and consistent than at other stations (Beckert, 1999).

The daily sediment record for the East Dubuque station began in 1943 and was maintained in paper form until 1967. During this period, the sediment yields were calculated from the sediment concentration and the discharge at East Dubuque. The discharge was based on stage height using a rating curve. Typically, data for the winter months (December-February) are unavailable though monthly sediment loads for these months are computed using a sediment rating curve (pre-1967) and a suspended sediment computer program developed by Sullivan in 1970. Beginning in water year 1968, the data have since been maintained in electronic format. Appendix A lists the percentage of daily data available during the length of the record for the entire year and for the period of March-August of each

year. Of particular note are the missing data for 1967 and the missing data during some of the extreme events such as the floods of 1965 and 1993.

Water discharge data from U.S.G.S. gages on the Mississippi River were used in this study primarily to determine the timing of specific discharge events in relation to the daily sediment concentrations that were measured independently at East Dubuque. Since there is no long-term discharge gage at East Dubuque and because sediment yields there have been determined from using more than one discrete discharge range, it is important to establish a discharge reference for the entire record. Two long-term stations are readily available for use as a reference: Clinton, Iowa and Mcgregor, Iowa. The gage at Clinton is 68 river miles downstream from East Dubuque. This reach includes the confluence of three significant tributaries: the Apple, Plum and Maquoketa Rivers. The gage at Mcgregor is 54 river miles upstream and does not include the influence of loadings from four major tributaries: the Wisconsin, Turkey, Platte and Grant Rivers.

For this study, the Clinton discharge data were used as the primary means of establishing discharge events based on criteria discussed in the methods section below. These were chosen for two reasons. First, the flow at Clinton is inclusive of the flow that passes East Dubuque. Secondly, the tributaries between the Clinton and East Dubuque stations are of less significance than the discharge from major tributaries like the Wisconsin and Turkey Rivers. It is important, however, to recognize the temporal relationship between sediment concentrations at East Dubuque and Clinton so a time lag has been estimated for peak flows at East Dubuque versus peak flows at Clinton. This estimate is based on comparing daily discharge from 1943-1996 between Clinton and Mcgregor (Figure 6). The

time lag between peak flows was calculated for a variety of different flow levels and shows a significant difference in lag from moderate flows to high flows. A proportional distance factor of 0.56 was established based on the relative position of East Dubuque between Mcgregor and Clinton. The result is a time lag between 1.06 and 1.74 days for the upper 10% of all flows relative to Clinton. This includes all flows above 95,000 cubic feet per second (cfs) at Clinton. The calculated time lag represents the average time between a significant discharge event East Dubuque and the same event downstream at Clinton. Calculation of this time lag was limited to higher discharges because the focus of the analysis is on the response of sediment concentrations during these higher discharge events.

MacGregor-Clinton Discharge Lag
(WY 1943-1996)
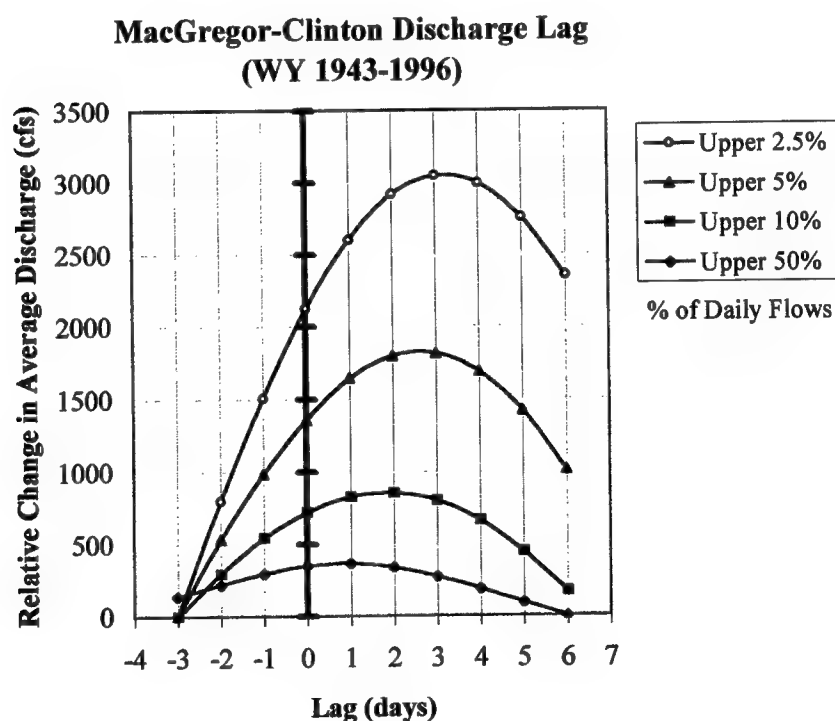
Figure 6. Peak discharge lag between U.S.G.S. gages at Mcgregor and Clinton, Iowa (data source: U.S. Geological Survey, daily discharge data wy1943-1996).

Discharge data for the Turkey, Platte and Grant Rivers were also used to examine the influence of nearby tributaries on sediment concentrations. Large discharges from these rivers were examined in conjunction with sediment concentrations in an effort to analyze the cause of strong residuals not explained by discharge values at Clinton. The Turkey River is of particular significance because of its proximity to the thalweg and the sediment that has been disposed near its outlet.

Climate data were analyzed to examine temporal trends in the frequency of storms and to separate snowmelt induced discharge events from storm induced events. Daily precipitation data for ten stations distributed across the drainage basin (Figure 2) were examined to determine the frequency of precipitation events of one inch or more during the spring and summer seasons from 1949 to 1996. The criteria for selecting these stations were the length of the record, percentage of data available and their spatial distribution. To distinguish snowmelt and storm runoff, winter and spring temperature data and snowpack conditions were analyzed. Average monthly temperatures and snow depth for February, March and April in Wisconsin and Minnesota were used to estimate likely timing of snowmelt events. Historical snowpack conditions for Wisconsin were examined to see likely potential for an event.

METHODS

A variety of techniques was used to analyze the lengthy and partially incomplete East Dubuque sediment record. A discussion of the details of these methods is important for similar studies to reproduce results comparable to those found by this study. This section includes a discussion of the assumptions made as well as the limitations inherent in an analysis of this nature. Specific details and examples of methods are included to illustrate not only how this study was performed, but also to show the errors and inconsistencies associated with averaging data over time and drawing conclusions about spatial relationships.

The analysis of the East Dubuque sediment record is based on several assumptions. Perhaps the most fundamental assumption is a result of limiting the study in time and scope. By limiting the study to only major hydrologic events, much of the variability imposed by local events can be eliminated. This is especially important because of the spatial separation of the discharge data and the sediment data. The first assumption is that the tributaries between East Dubuque and Clinton have only a minor effect on the hydrograph during extreme events. Additionally, an assumption has been made about the periods in the year for which data would likely reveal significant trends. The conditions during the winter and fall represent only minor periods of sediment transportation. Thus, this study is limited to the spring and summer months (March – August). As discussed previously, a third assumption has been made about the time lag between discharge peaks at the two stations. This time lag is assumed constant over the course of the record and during events of similar magnitude. These assumptions are necessary for relating discharge events to sediment concentrations.

Another important assumption is the homogeneity of the sediment concentration record over time. Over the course of 54 years, several significant changes in sampling have likely occurred that are not documented with the data. These include changes in equipment used and sampling techniques as well as changes in the individual observer. These are potentially significant sources of errors in measuring sediment concentrations. In terms of equipment and techniques, standard U.S.G.S. techniques have been employed since the early 1940s (Mack, 1970), but the actual person taking the measurements has changed. While this could possibly result in significant errors of measurement, the assumption is made that the errors imposed over time are not significant enough to affect the homogeneity of the record.

Several limitations of this study are also recognized. First is the availability of the data. Data for winter months are generally unavailable, as are data during important hydrologic events such as the floods of 1965 and 1993. While winter data are likely insignificant, information from large events such as these is key when establishing a statistical relationship based on few data points. Another limitation is the gross averaging of the data based upon inconsistent time intervals. The difficulty in separating individual events from the hydrograph of a river as large as the Mississippi makes it necessary to also examine the data averaged over arbitrary time intervals as a way of comparing the results.

The initial examination of the data included a qualitative analysis of discharge data over the period and sediment concentrations over the period. Daily discharges were transformed using a log transformation to normalize the data. These data were then averaged by season and converted to z-scores to compare seasonal, annual and decadal variability to

variability in average sediment concentrations. From this analysis, several periods were identified as being significantly wet and dry, particularly on annual and decadal timescales.

Two primary modes of analysis were employed to examine sediment concentrations. The first is an analysis of sediment concentrations during individual discharge events over the course of the record. The other mode is the analysis of average weekly sediment concentrations as a function of time and discharge. Alternative methods were used as a tool for comparison of sediment concentration trends over time. These methods were expected to achieve similar results in terms of the functional relationship of sediment and discharge over time. A closer examination of these methods follows.

As previously discussed in the sediment transport section, there is a distinct relationship between the hydrograph of stream flow and the movement of sediment. An examination of sediment concentrations during peak discharges of the Mississippi River should reflect this relationship and changes in it over time. So criteria were established for determining discharge event type and magnitude. The discharge hydrograph was examined and average sediment concentrations were divided into two groups. Group 1 consists of snowmelt events and Group 2 consists of storm events. Typically, the snowmelt event is the first significant event in the spring. It has a gently sloping rising limb and lasts, in terms of the Mississippi River hydrograph, a few weeks to over a month. To separate snowmelt events from storm events, April 7th was chosen to represent the latest likely date of separation between an event that was caused by snowmelt and one that was caused by storm runoff. This date is based intuitively on the snow record from 1961-1977 (Figure 4) which indicates the period of greatest snowmelt sometime between the period of March 16th to April 7th. This

date serves as a starting point to determine whether an event was caused by snowmelt. Temperature and snowpack records of Wisconsin and Minnesota were next examined to fine-tune this date in conjunction with an examination of the discharge hydrograph. Snowmelt events were then separated into two discharge categories: low and high magnitude events. An arbitrary discharge rate of 120,000 cfs was used to separate snowmelts into roughly two equal groups. A minimum threshold value of 65,000 cfs was established to remove insignificant snowmelts. This technique resulted in a total of 14 low events and 19 high events.

For storm runoff (Group 2), discharges were divided into three categories. Arbitrary thresholds were chosen to facilitate this. These thresholds represent distinct discharge rates that have been classified as low, moderate and high discharge events. Low discharge storm runoff typically occurs one or two times during the spring and summer of each year and produces discharge rates between 90,000 and 125,000 cfs. A moderate discharge occurs about every other year with a discharge between 125,000 and 150,000 cfs. Finally, high discharges over 150,000 cfs are somewhat rare, and thus occur on average once every three or four years. Individual discharges were analyzed in terms of the length of the event. The standard for this was based specifically on the rising and falling limbs of the hydrograph. Averaging periods start with the first day of increase on the rising limb of the hydrograph and continue through the last day of the falling limb. This technique highlights the time averaging limitation previously discussed because the durations of storm or snowmelt runoff are different. Table 2 lists the general statistics of Groups 1 and 2 in terms of total number of

	Event Group				
	Group 1 (snowmelt)		Group 2 (storm)		
	low (65-120k cfs)	high (>120k cfs)	low (90-125k cfs)	moderate (125-150k cfs)	high (>150k cfs)
sample size	14	19	33	25	15
mean length of averaging period (days)	41	45	23	27	31
std dev of averaging period (days)	10	11	9	8	11

Table 2. Averaging statistics for Groups 1 & 2.

events, average length of the events and the standard deviation of the length of the events.
This averaging problem led to further examination of data in terms of peak sediment
concentrations during a flood and averaging the data over a fixed time period (Group 3).

Another problem is the recovery time from one event to another. Many of the
hydrographs examined had a series of discharge peaks closely following one another. To
account for this in the analysis, events were also coded by recovery time. These were also
arbitrarily determined and divided into three categories: short, moderate and long recovery
periods. Periods are identified as short if less than 15 days, moderate if between 15 to 30
days and long more than 30 days. Recovery periods were measured on the hydrograph peak
to peak. Table 3 summarizes the number of events in each category.

The problems associated with analysis of sediment concentrations in terms of the
rising and falling limbs of the hydrograph are many. Averaging periods vary, separating
individual events is ambiguous and analyzing the effect of recovery period is difficult. To

Event Category	Recovery Periods		
	Short (<15 days)	Moderate (15-30 days)	Long (>30 days)
Low (90-125k cfs)	11	12	10
Moderate(125-150k cfs)	16	8	1
High(>150k cfs)	8	4	3

Table 3. Frequency of recovery categories for Group 2.

eliminate the many problems associated with the rising limb-falling limb approach, Group 3

consists of a weekly averaging approach as an alternative. This method looks at the weekly

average sediment concentrations measured at East Dubuque as a function of time and weekly

average discharge at Clinton, Iowa. A one-week interval was chosen as an appropriate time

interval because it is smaller than the average interval of a discharge event on the Mississippi

River, yet it allows significant averaging of individual outliers. This method ensures all

values are based on the same period of averaging and eliminates the need to consider

recovery. Weekly concentrations can also be grouped by months allowing an analysis of

sediment variation over the course of the spring-summer seasons. However, the critical

drawback to this method is that the sediment sampling site and discharge site are not co-

located. Thus, discharge events occurring downstream from the sediment sampling site are

being included in the model imposing an error on the functional relationship.

The data grouping methods listed above were subjected to basic statistical procedures.

For all data sets, sediment concentration was examined as a function of time in order to

detect temporal trends. Simple least squares regression analysis was performed on a log-

linear transformation of the data. Transformation of the dependent axis, specifically average

sediment concentration, was done for several reasons. First, the distribution of sediment data is positively skewed, even when only examining concentration during peak events. Secondly, the values for the concentration have a range of more than an order of magnitude. As an example, for peak sediment concentration during moderate magnitude events, values range from 80 to 3000 parts per million (ppm). Another characteristic of the data was heteroscedasticity. Figure 7 is an example of the residuals of sediment concentrations during moderate discharge events. The residual variance changes as a function of time. During the 1990s, variance of the residuals is much greater than during any other period of the record. Finally, the nature of the data itself requires a transformation of the dependent axis.

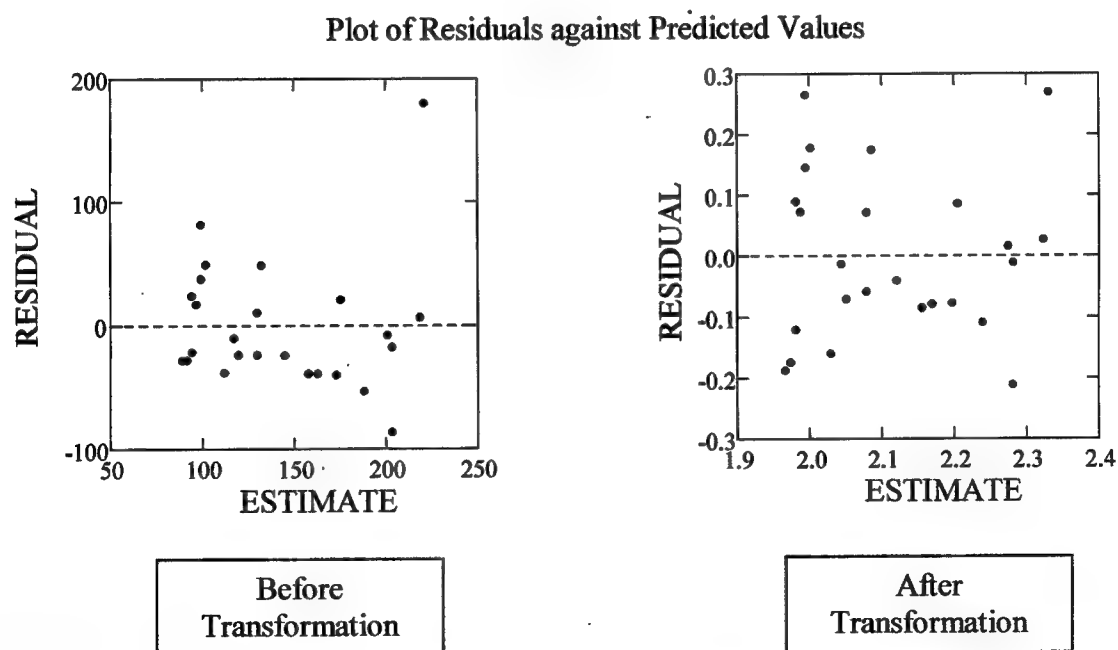Plot of Residuals against Predicted Values

Figure 7. Residual plot, before and after transformation.

Suspended sediment concentration cannot be a negative number, and a strictly linear regression would likely predict a trend that resulted in negative values over time.

The transformed concentration data were regressed against time using the ordinary least squares method. The regression model for this trend analysis is given by the equation:

$$Log\ (C) = \beta_0 + \beta_1\ (T),$$

where C is sediment concentration (ppm), and T is time (years). Additionally, for analyzing the influence of recovery time on sediment concentrations, a multiple regression model was used that included a recovery variable, R, such that,

$$Log\ (C) = \beta_0 + \beta_1\ (T) + \beta_2\ (R).$$

This analysis was conducted for all data groups. Regression graphs for all three groups were constructed for the simple regression model only. Several regression diagnostics were conducted to determine significance. Regression lines with confidence intervals at the 95% tolerance level were established. The coefficient of determination, r^2, was calculated to measure the fraction of the variance in sediment concentrations explained by the regression model. The F-test was conducted at the 0.05 level of significance to determine whether or not the relationship between sediment concentration and time is likely to occur purely by chance. Finally, the t-statistic for b_1 and b_2 was tested to determine if the coefficients of the

time and recovery variables are significantly different from zero. This was also conducted at the 0.05 level of significance. For example, if the slope of the time variable, T, is not zero, the null hypothesis of zero change in slope over time is rejected indicating that there is in fact a trend in sediment concentrations over time. Analysis of the residuals was conducted to explain outliers in the data. Strongly positive and negative residuals were examined in conjunction with tributary discharges, seasonal moisture conditions and seasonal timing.

Precipitation data were analyzed in a similar fashion to determine temporal changes in the frequency of storms of one inch or greater. Since these data are based on a standard 24-hour day, one inch storm events occurring over portions of consecutive days are not considered. Daily data from ten climate stations were analyzed by determining the frequency of spring and summer storms for each station from 1949-1996. The annual frequency of these storms was regressed against time and the t-statistic for the coefficient of time was tested at the 0.05 level of significance.

Finally, qualitative observations of the record were conducted. The response of sediment concentration to specific discharge events was compared graphically for different time periods. A comparison of sediment concentrations to seasonal moisture conditions was made to establish annual and decadal trends in sediment response. Additionally, concentrations and discharges were separated by decade and plotted graphically. This was done to express the evolution of the sediment transport regime in a quantitative way while allowing a qualitative analysis. This analysis aims at further understanding the relationship between sediment concentration and river discharge over a series of decadal time periods.

RESULTS

The significant findings from the analysis of the East Dubuque sediment data are presented in two sections: quantitative analysis and qualitative observations. The quantitative section offers an analysis of sediment response over the entire length of the record under several types of discharge regimes. The quantitative analysis discussed in the methods section was used as a basis to determine the level of significance of temporal sediment transport trends. By contrast, the qualitative findings are a presentation of observable trends from an examination of the long-term discharge and sediment records. This technique allows an analysis that is somewhat subjective but broader in scope than a strictly numerical analysis. Also specific examples are identified that are useful in visualizing relationships and understanding trends in the record as a result of changes in both land management and climate regime. The final part of this section is a discussion of the overall decadal trends discovered as a result of both the qualitative and quantitative analyses.

QUANTITATIVE ANALYSIS

The regression model discussed in the methods section was used for several different groups of data based on the grouping methods used. Group 1 consists of sediment concentrations averaged over the course of snowmelt events divided into two sub-groups: low and high magnitude snowmelt runoff. Group 2 consists of sediment concentrations during storms divided into three categories: low, moderate and high magnitude storms. These groups were further subdivided into average and peak sediment concentrations.

Finally, Group 3 consists of the weekly averaged data. Group 2 shows the most significant trends, especially during medium and high magnitude storms. Group 1 shows a significant trend for high magnitude snowmelt runoff. Group 3 shows a slightly decreasing trend over time. In general, temporal trends are strongest for the higher energy events and weak or non-existent for low energy events and for the data averaged independent of hydrologic events.

Group 1 consists of average sediment concentrations for snowmelt runoff above a threshold value of 65,000 cfs for both low magnitude (<120,000 cfs) and high magnitude (≥120,000 cfs) runoff. The model fit for this group is shown in Figure 8. In analyzing all of the regressions, environmental changes are assumed the essential factor driving changes in sediment concentrations. Table 4 lists the regression summary for Group 1. For the high magnitude snowmelt runoff, environmental changes over time explain 54% of the variance of sediment concentrations while only 27% is explained by environmental changes for low flows. This difference between high and low runoff conditions is generally true for the regressions of the other groups as well. Sediment concentrations for lower discharge conditions appear to be much less predictable than the high magnitude runoff, though the regression slopes are almost identical.

For low magnitude snowmelt runoffs, average sediment concentrations have decreased from about 100 ppm in the 1950s to roughly 50 ppm in the 1990s. An examination of the residuals reveals two strongly positive residuals. The first was during the snowmelt event of 1953. The sediment spike for this event appears to be a severe aberration with values above 3000 ppm. It is associated with relatively low flows of the Turkey, Platte and

	Group 1 (snowmelt)	
	low (65-120k cfs)	high (>120k cfs)
sample size	14	19
r^2 (adj)	0.273	0.543
standard error	0.197	0.111
regression equation	Log(C)= 16.487-0.007(T)	Log(C)=17.540-0.008(T)
P (t-stat), b_0 0.05 level of significance	0.018	0.000
P (t-stat), b_1 0.05 level of significance	0.032	0.000

Table 4. Regression Summary for Group 1 (Note: all data are in log units).

Grant Rivers indicating that local tributaries are not influencing the concentration. Another unusual aspect of these sediment peaks is that they came on the falling limb of the hydrograph. Possible explanations include measurement error, dredging-induced sediment slugs or perhaps the result of a strong prevailing wind oriented along the pool upstream of Lock and Dam 11. The other positive residual occurred in 1974 and is associated with high discharges from local tributaries. The discharges from these tributaries appear to be storm runoff although the basin as a whole is providing primarily snowmelt runoff. This residual highlights the heterogeneity of runoff types in a large basin and the inherent weakness in creating dichotomous runoff categories.

Snowmelt with runoff over 120,000 cfs is better predicted by the regression than any other group analyzed. Part of the reason is the averaging technique itself. Sediment concentrations are averaged over the course of an event. Large snowmelt discharges are of long duration, typically lasting about 45 days in the case of the Mississippi River hydrograph.

Additionally, these flows have the energy to generate sediment while the variability imposed by the erosive forces of rainfall is absent. Several negative residuals are present in this group, possibly a result of being averaged over a slightly longer time period. Three of the four residuals were averaged over about 50 days.

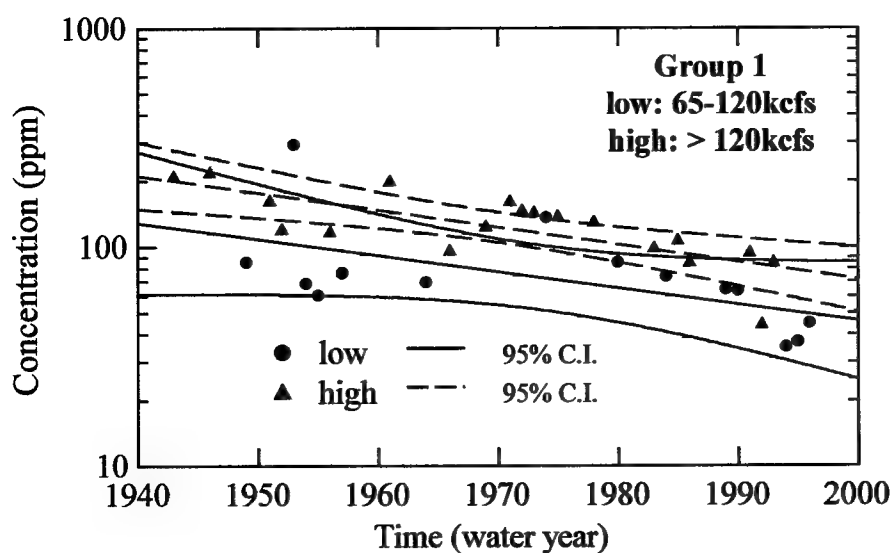**Figure 8. Regression of snowmelt runoff (Group 1).**

Group 2 consists of sediment concentrations as a function of storm runoff events that were divided into three magnitude categories. Each category includes regressions for average and peak flows. The results are summarized in Table 4. The variability of average and peak sediment concentrations is not well explained for low magnitude runoff. For

moderate and high magnitude runoff, the regression model explains about 40% of the

variability of average sediment concentrations and between 39-50% of the variability of peak

sediment concentrations. The test for significance of the coefficient of time indicates that in

all cases the slope is significantly different than zero and a temporal trend exists. Likewise,

for all cases, an evaluation of the F-statistic suggests that the regression relationship between

time and sediment concentration is not a result of chance alone.

Group 2 (storm)							
category		n	r^2 (adj)	std. error	regression equation	P (t-stat), b_o 0.05 level	P (t-stat), b_1 0.05 level
low (90-125k cfs)	Avg.	33	0.240	0.158	Log(C)=12.967-0.006(T)	0.000	0.002
	Peak	33	0.225	0.281	Log(C)=21.209-0.010(T)	0.001	0.003
moderate (125-150k cfs)	Avg.	25	0.424	0.139	Log(C)=15.911-0.007(T)	0.000	0.000
	Peak	25	0.389	0.283	Log(C)=28.801-0.013(T)	0.000	0.001
high (>150k cfs)	Avg.	15	0.402	0.499	Log(C)=15.455-0.007(T)	0.002	0.007
	Peak	15	0.162	0.277	Log(C)=29.699-0.014(T)	0.001	0.002

Table 5. Regression summary for Group 2 (Note: all data are in log units).

The regression of average and peak sediment concentrations for low magnitude storm

runoff is presented in Figure 9. Both graphs exhibit similar trends, with sediment peak

concentrations decreasing more rapidly over time than average sediment concentration. Two

strongly negative residuals for average and peak concentrations in 1952 and 1965 are

possibly the result of the timing of their associated storms. Both occurred during summer
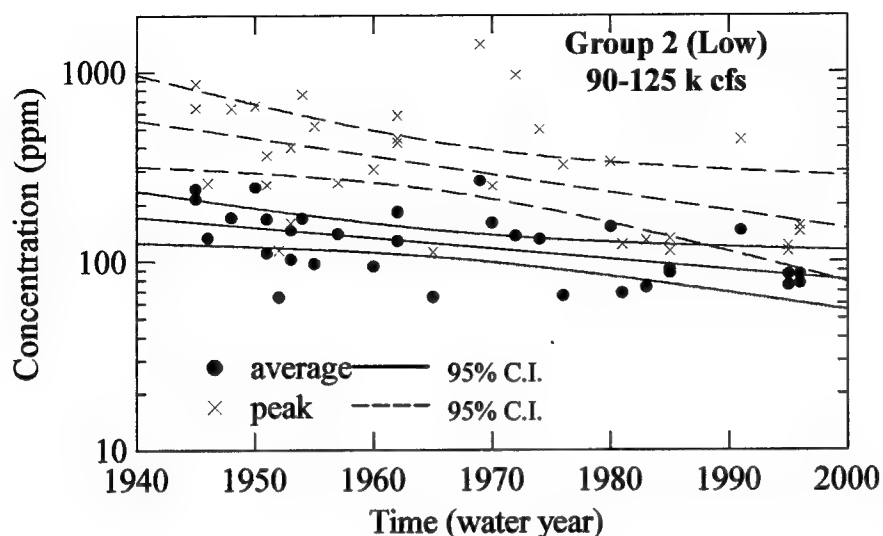
Figure 9. Regression of low magnitude storms runoff (Group 2).

months or periods of high vegetative cover and both were associated with relatively small flows from the Turkey River. The other tributaries of the Platte and Grant Rivers had relatively higher flows. By contrast, the strong positive residual occurring in 1969 occurred in summer in conjunction with high magnitude flows from the Turkey River, while the Platte and Grant River flows were relatively moderate. This observation brings into question the importance of the Turkey River flows versus the Grant and Platte Rivers. The proximity of the thalweg near the outlet of the Turkey River and the history of dredging operations occurring in this vicinity may play an important role in the addition of transportable sediment into the Mississippi.

Figure 10 shows temporal changes in sediment concentration over the record for moderate levels of discharge. Again, the peak sediment concentration is shown to be decreasing at a slightly greater rate over time than is the average sediment concentration.

Negative residuals for both cases are associated with relatively low flows for the nearby

tributaries. Two strongly positive residuals occurred in the case of peak sediment

concentration in 1983 and 1991. In the latter case, it was associated with high local tributary

discharge. The 1983 residual occurs on the falling end of the hydrograph and is not

associated with high tributary flow. It is possibly the result of some other disturbance on the

Mississippi or possibly the result of an error in measurement.

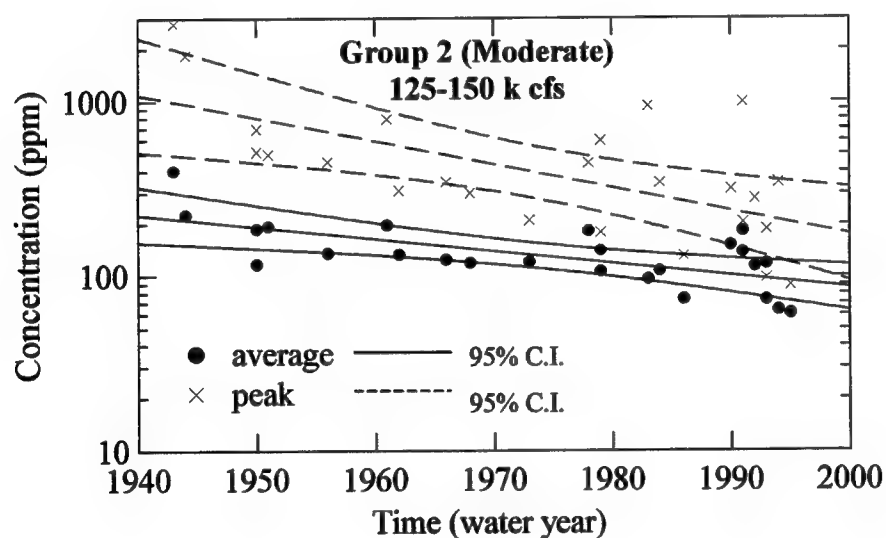**Figure 10. Regression of moderate magnitude storm runoff (Group 2).**

The final category in Group 2 is the high magnitude sediment concentrations.

Though this group has a similar regression fit as the moderate category, the small number of

cases (15) makes it less reliable. Again, this regression shows a similar trend in both average

and peak sediment concentrations, and the trends are comparable to those for the moderate

magnitude concentrations (Figure 11). The one strongly positive residual, in 1974, is the result of two intense storms occurring within a week, generating concentrations that were averaged over a relatively short time interval. The effects of the storms can be seen distinctly on the tributary hydrographs as very high discharges. However on the Mississippi River hydrograph, they are difficult to separate and they are included as one event.

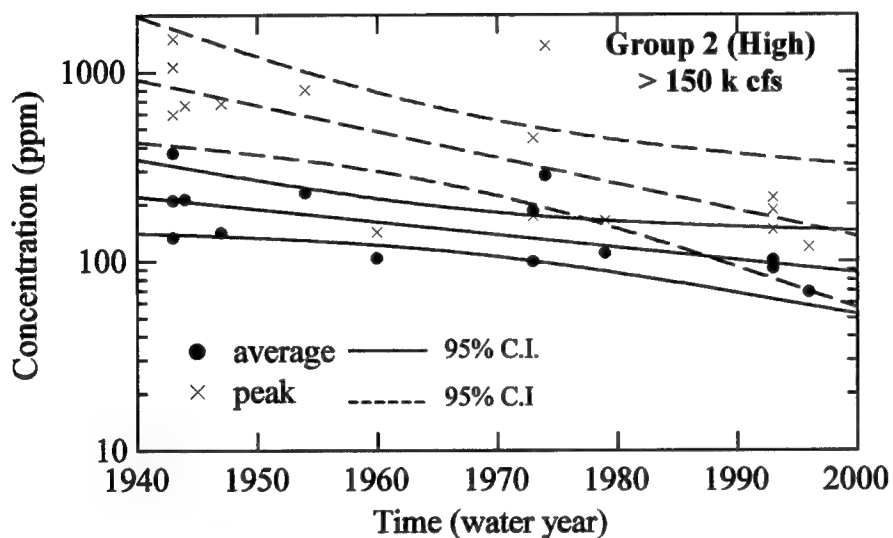**Figure 11. Regression of high magnitude storm runoff (Group 2).**

The analysis of temporal changes in storm frequency suggests that the role of climate change as an influence on sediment concentrations has been minimal. The frequency of spring and summer storms with rainfall magnitudes of one inch or more has not changed significantly over the period from 1949 to 1996. However, the frequency has varied

dramatically from year to year. For all ten stations, the test for significance indicates that the coefficient of time is not significantly different than zero (Table 5). Previous studies in the region have shown similar results. Karl's (1984) analysis of climate change in North America in the 20th century identified annual and decadal variability in precipitation at individual stations and between nearby stations, but did not determine a specific long-term trend in precipitation. Baker (1990) analyzed storm rainfalls ≥ 1.0 inch in the Galena watershed in southwest Wisconsin from 1940-1987 and showed no statistically significant trend occurred during this period.

Frequency of Precipitation Events ≥ 1.0" (1949-1996) Spring-Summer Seasons (n =48)					P (t-stat) 0.05 level		Regression Equation
State	Station Name	Mean	r^2 (adj)	Std Error	b_0	b_1	
IA	Decorah	5.3	0.000	2.219	0.309	0.367	Y=46.873-0.021(T)
MN	Artichoke Lake	3.9	0.000	1.855	0.428	0.488	Y=30.512-0.014(T)
MN	Faribault	4.6	0.000	2.283	0.375	0.430	Y=42.010-0.019(T)
MN	Milaca 1 ENE	4.6	0.010	2.062	0.192	0.230	Y=56.010-0.019(T)
MN	Walker AH	3.8	0.017	2.237	0.158	0.183	Y=66.015-0.032(T)
WI	Blair	5.3	0.000	2.201	0.769	0.858	Y=13.387-0.004(T)
WI	Cumberland	4.8	0.000	2.279	0.716	0.794	Y=17.125-0.006(T)
WI	Lancaster 4 WSW	5.0	0.000	2.403	0.769	0.846	Y=14.594-0.005(T)
WI	Mauston 1 SE	4.4	0.000	2.150	0.656	0.729	Y=19.792-0.008(T)
WI	Spirit Falls	4.1	0.000	2.026	0.876	0.953	Y=6.525-0.001(T)

Table 5. Frequency of storms (≥ 1") for select climate stations (data source: National Climatic Data Center, summary of the day, Earthinfo, Inc.).

Overall, the regression models indicate that the response of sediment concentrations to storm runoff has significantly decreased over the last half century. Peak concentrations in storm runoff have decreased from about 1000 ppm in the 1940s to about 200 ppm in the 1990s. Average concentrations have likewise decreased from about 200 ppm in the 1940s to 100 ppm in the 1990s. These decreases are occurring under similar precipitation conditions, indicating that other environmental changes in the basin are affecting suspended sediment concentrations. The most significant environmental change in the Upper Midwest since the 1940s has been the widespread adoption of land conservation in terms of land use and land management practices (Knox, 1977; 1987; Trimble and Lund, 1982; Baker, 1990; Argabright, *et al.*, 1996).

Recovery periods for events were also examined in all Group 2 categories by using a multiple regression model. In all but one case, the coefficient of the recovery variable had a high probability of not being significantly different from zero and was rejected. In the case of average sediment concentrations during low magnitude events, recovery time is significantly related based on the t-statistic ($p = 0.034$). Overall, based on the inconsistencies across the various categories, the statistical significance of the recovery variable is inconclusive. In the case of the Mississippi River hydrograph, the actual recovery time is virtually impossible to determine because of the heterogeneity of the spatial variables across the basin. Recovery times may be meaningless in situations where local tributaries are providing large sediment pulses.

Group 3 consists of sediment concentrations averaged weekly for the spring and summer months. This group was made independent of discharge magnitude, so a wide range of averages has resulted. The input of these data into the regression model revealed a general downward trend, but did not explain the variance in the data (Figure 12). This method of analyzing the data was not useful in determining a statistical relationship between sediment concentrations and changing environmental conditions over time. The reason is the inclusion of two significant and often opposing environmental parameters: land use and climate. While conservation-oriented land use has improved continually over the last 54 years, changes in precipitation patterns have fluctuated on annual and decadal timescales. The timing of storms throughout the growing season and annual variability of wet and dry
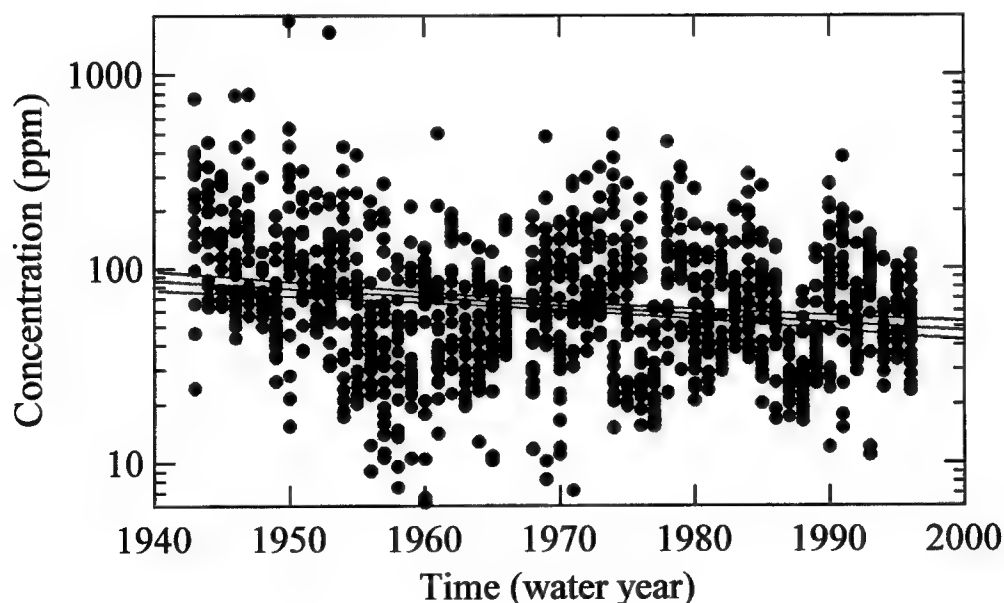

Figure 12. Regression of weekly average sediment concentrations (Group 3).

conditions makes discovering a relationship difficult without separating the two parameters.
However, by analyzing sediment concentration as a function of time and discharge, a general
relationship can be developed using multiple regression. Table 7 shows the regression
statistics for a multiple regression model for average weekly sediment concentrations as a
function of average weekly discharge and time such that:

$$\text{Log}(C) = \beta_0 + \beta_1(T) + \beta_2 \text{Log}(Q)$$

where C is the sediment concentration (ppm), T is time (years) and Q is the stream discharge
(cfs). This regression model explains 48% of the variability in sediment discharge and has
similar coefficients to the regression equations for Group 2. These weekly averages show
significant annual and decadal variations, as well, and were useful in examining trends in a
qualitative sense. An explanation of these trends is included in the next section.

	Group 3 (weekly average sediment concentrations)
sample size	1272
r^2 (adj)	0.480
standard error	0.242
regression equation	$\text{Log}(C) = -2.078 - 0.005(T) + 0.891\,\text{Log}(Q)$
P (t-stat), b_0 0.05 level of significance	0.000
P (t-stat), b_1 0.05 level of significance	0.000
P (t-stat), b_2 0.05 level of significance	0.000
standardized coef., b_1	-0.227
standardized coef., b_2	0.664

Table 7. Regression summary for Group 3 (Note: all data are in log units).

QUALITATIVE OBSERVATIONS

The visual examination of the entire data record is logically the first step in any trend analysis. While not always conclusive, it serves as a guide and helps limit the scope of further analysis. This was the case for analyzing the sediment record at East Dubuque. The lack of significant discharges and sediment concentrations during the fall and winter months encouraged a more careful examination of the spring and summer data. As discussed in the methodology section, two different grouping methods were used to determine time intervals for averaging sediment data. The grouping method used for Groups 1 and 2 was based on the rising and falling limbs of the hydrograph during times of above average runoff. The results from this method were the basis for the quantitative analysis. In contrast, the weekly averaging method provided little information in terms of accounting for the variability of

sediment concentrations in a quantitative sense. However, an examination of the weekly average sediment concentrations for spring and summer over the course of the record proved interesting. When compared to the seasonal discharge variability at Clinton, the weekly sediment averages reveal notable decadal variability as shown in Figure 13.

During the 1940s and early 1950s, seasonal discharges were relatively average with a few significantly above average fluctuations. Weekly sediment concentrations during this period were some of the highest on record, often exceeding 200 ppm. These high sediment rates during this period are not unexpected based on the land use record and often cited lag between the initiation of conservation practices and the observation of reduced sediment yields (Trimble and Lund, 1982; Knox, 1977). The mid-1950s to the mid-1960s was a period of below average seasonal discharges, associated with a corresponding reduction in sediment concentrations. Thus, average sediment concentrations during this period are likely a result of reduced flows and, to a lesser degree, conservation measures. The mid-1960s to the mid-1980s represents a period of alternating wet and dry seasons with several seasons of extreme discharges such as the springs of 1965, 1973 and 1982. This period correlates to a similar period of high average sediment concentrations, generally around 80-100 ppm. Despite the frequency and magnitude of high seasonal discharge well in excess of discharges during the mid 1940s to early 1950s, sediment concentrations are significantly lower.

The reduction in sediment concentrations from the 1940s to the 1970s can be attributed to land conservation efforts in the uplands and a reduction of sediment availability in the valley bottoms as well. Trimble and Lund (1982) determined that upland erosion in the Coon Creek Basin decreased dramatically from 1940 to 1970 because of improved land
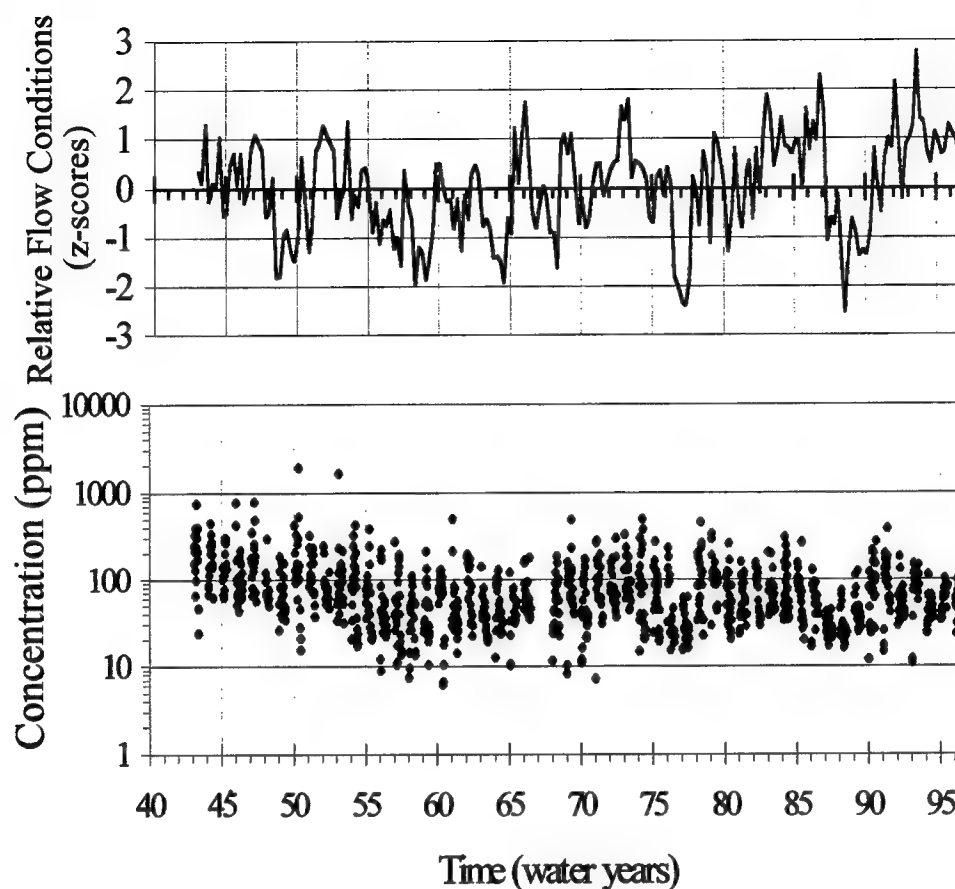
Figure 13. Records of seasonal (Winter, Spring, Summer and Fall) discharge variation from the mean (Clinton, IA) and average weekly sediment concentrations (East Dubuque, IL).

management. Baker (1990) determined that from 1940-1987 land use under soil

conservation practices in the Galena watershed increased from 37% to 85% resulting in less

erosion. Another important conservation measure that contributed to the decrease in upland

erosion was the increase in corn planting density. The use of herbicides and pesticides

beginning in the 1950s reduced the requirement for cross cultivation of corn for weed control. This not only promoted an increase in crop density but also dramatically reduced extreme rill erosion associated with up and down slope cultivation. The increased crop density protects the soil from sheet and rill erosion as well as from the impact of rain droplets (Knox, 1998).

The mid-1960s to mid-1980s period also included significant periods of low discharge, particularly 1976. In this year, weekly sediment concentrations were around 20-30 ppm during the spring and summer. These values are some of the lowest concentrations on record for these seasons, well below sediment concentration during the dry period of the late 1950s and early 1960s. The late 1980s is another period of continuous below normal discharges with sediment concentrations clustered in a similar fashion to the 1976 sediment concentrations. Finally, the 1990s represent a period of higher than normal seasonal discharges, particularly 1991 and 1993. This period has sediment concentrations averaging about 50 ppm, well below the 1940s values of 100-200 ppm and significantly below the 1970s values of 80-100 ppm. This further decrease in sediment concentrations may indicate a further reduction in the sediment delivery to the Mississippi River.

To visualize long-term temporal trends in sediment concentration better, an example is offered that contrasts the sediment response to similar discharges during three specific years: 1944, 1972 & 1992. These particular years were chosen based on several criteria including similarity of discharge regimes (including nearby tributary discharges), preceding snowmelt levels and data availability. Figure 14 depicts the relationship between sediment

Sediment Peaks During Similar Flows
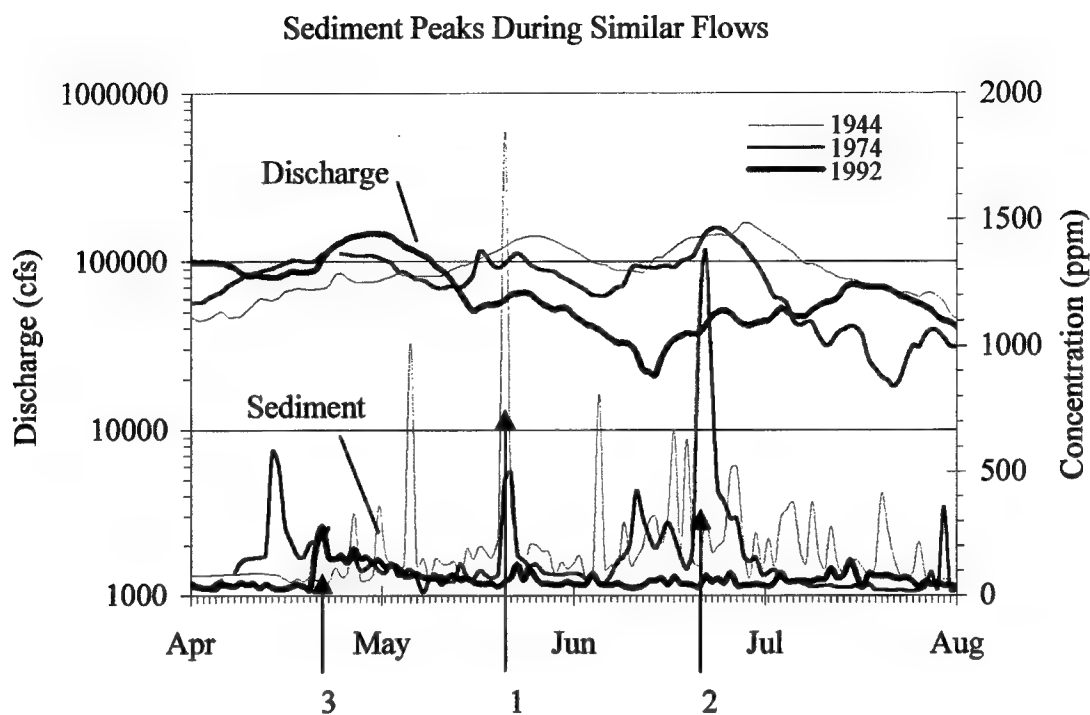
Figure 14. Sediment concentrations during similar flows: 1944, 1974 & 1992.

concentrations and discharge from the beginning of April to the end of July for the three

years. The first notable feature of the entire record is the variability of sediment

concentrations. In 1944, sediment concentrations vary widely, peaking over 500 ppm five

times along with many other significant peak concentrations. In 1974, sediment

concentrations are significantly less variable and peaks are significantly lower in magnitude

with only three above 500 ppm. By 1992, the fluctuations in sediment concentrations are

minor by comparison, with all peaks below 300 ppm.

For each year, a specific event is identified with a numbered arrow. In 1944, a discharge event with a peak discharge of just over 140,000 cfs coincided with a massive sediment peak of 1800 ppm (arrow 1). A similar discharge in 1974, slightly less than 160,000 cfs, resulted in a concentration peak of just under 1400 ppm (arrow 2). Finally, in 1992, a discharge peak of about 145,000 cfs was associated with a sediment concentration peak of only 280 ppm (arrow 3). Clearly, a general decline in the sediment concentration is occurring over time. These examples support the idea that sediment concentrations have decreased greatly since measurement began in the early 1940s.

Based on subjective observation, sediment concentrations have evolved over the course of the last six decades. Over that period, concentration peaks have decreased in magnitude and variability. The suspended sediment regime in the Mississippi River has shifted from a regime of rapid response to changing discharges to a regime of relative constancy. This implies that future sediment concentrations should be more predictable.

DECADAL TRENDS

From the quantitative and qualitative analysis, it is evident that several alternating trends have occurred in terms of sediment concentrations as a function of seasonal climate and land management. These trends are observable from the qualitative approach as shown in Figures 13 & 14. However, quantitatively these trends are difficult to present in a visual form. Figure 15 is an effort to provide a general quantitative representation of these decadal trends. This graph is a plot of average monthly sediment concentrations against average monthly discharges for the spring and summer months by decade. For each decade, a linear

regression line has been drawn. Though the regressions explain only from 20% to 50% of

the variability of the sediment concentrations, this graph is useful in showing the evolving

relationship of sediment concentrations to discharges over the record.

Sediment Concentration vs Discharge (Spring-Summer)
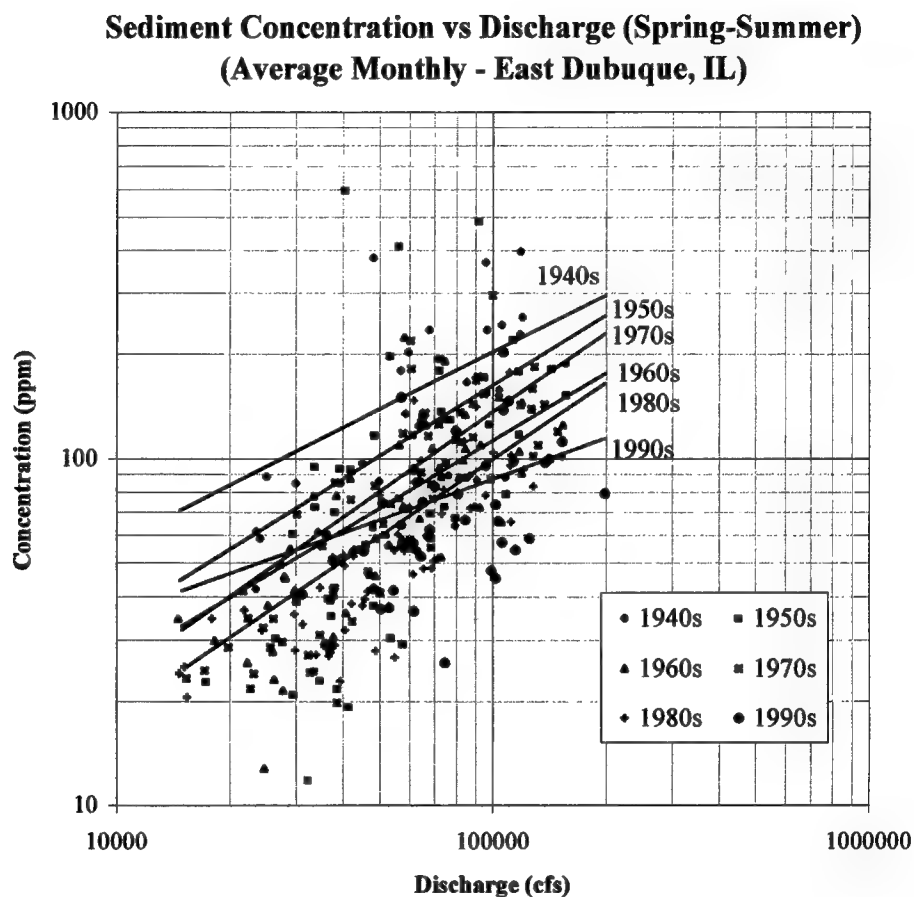**(Average Monthly - East Dubuque, IL)**

Figure 15. Decadal trends in sediment concentrations.

The decrease in average monthly sediment concentrations from the 1940s to the

1990s is apparent. However, the trend is not continuous. The trend for the 1940s and 1950s

shows sediment concentrations are at the highest levels of any decade. As discussed

previously, this is likely a result of a combination of easily transportable soil and average to above average discharge conditions. The 1960s show a distinct decline in sediment concentrations attributed in part to reduced flow conditions. It must be reemphasized, however, that concentration data for the flood of 1965 and the entire year of 1967 are not available. Thus, the possibility of error is greatest for this decade. The 1970s reflect a period of high discharges resulting in high sediment concentrations, though not as high as levels during the 1940s and 1950s. The period of the 1980s and 1990s shows very low average concentration levels for the spring and summer months. The 1980s results are likely a function of decreased discharge and a reduction in sediment availability while the low levels of the 1990s are due primarily to a lack of sediment availability during high discharges.

Based on these decadal trends and their associated driving mechanisms, several hypotheses are suggested for future sediment conditions in the Upper Mississippi River. For dry conditions in the future, the river should experience a significant reduction in sediment concentrations. These reductions will be a result of both the low discharge and continued flushing of sediment from the drainage basin. If the next decade is extremely wet, a change in the average sediment concentrations will be harder to detect and would resemble the current trend for the 1990s. Higher flows have the potential to remobilize stored sediment and increase the variability of suspended sediment in the system.

CONCLUSIONS

The analysis of the sediment record at East Dubuque provides insight on temporal trends of sediment transport in the Upper Mississippi River Basin. This study shows that significant decreasing trends in sediment concentrations exist for several different flow regimes. Concentrations have decreased most significantly for periods of high flow such as during high magnitude snowmelt runoff and moderate to high magnitude storm runoff. From the 1940s to the 1990s, average concentrations during these flows have decreased from about 200 ppm to less than 100 ppm. Similar trends were observed for peak sediment concentrations during these runoff events as well. An analysis of the frequency of spring and summer storms of one inch or more revealed no significant trend from 1949 to 1996 for ten climate stations throughout the basin. This suggests that the role of climate change in influencing sediment concentrations over the last five decades has been minimal. Therefore, temporal trends in sediment concentrations are likely the result of widespread adoption of soil conservation practices in the last half-century coupled with higher density planting of row crops.

Analyses of residuals for regression equations that describe temporal trends in sediment concentration indicate that local conditions have a significant impact on measured concentrations. Tributaries immediately upstream of the measuring station experienced discharge peaks in conjunction with anomalous sediment concentration spikes. The Turkey River appears to have a stronger relationship in this regard than the Platte or Grant Rivers despite its greater distance from the measuring station. Possible factors for this are the

Turkey River's direct connection to the thalweg and minor influence from historical dredging operations near the Turkey River's outlet.

The sediment-discharge relationship exhibited decadal trends of sediment concentrations as a result of annual and decadal climate variability. The 1940s and 1950s exhibited high sediment concentrations for all flow conditions. During the 1960s, when conditions were relatively drier, sediment concentrations were significantly lower. However, in the 1970s and early 1980s there was a shift back to wetter conditions and an associated increase in sediment concentrations. The late 1980s brought about a shift to much lower sediment concentrations as a result of generally drier conditions. Despite a transition to relatively wetter conditions in the 1990s, sediment concentrations for high discharges have remained low, though average concentrations for lower levels of flow have increased.

The impact of fluctuating sediment regimes is significant for a variety of functions that the Mississippi River provides. As a conduit of commerce, the river must continue to be assessed in terms of design criteria for future navigation projects and the maintenance of projects already in place. Managers of natural resources must consider the influence that shifting sediment regimes may have on aquatic habitat and water quality. These changing sediment transport relationships have a geomorphic implication as well. A long-term switch from one condition to another could elicit a corresponding response in the channel morphology over time. The results of this study serve as a starting point for future research in linking the variability of upstream sediment concentrations to downstream channel variations in morphology, sedimentation and erosion. Understanding the sediment regime in

the Upper Mississippi River basin today is important for studying future fluvial processes

occurring downstream, shaping a new course for a dynamic river system.

REFERENCES

Anderson, H.W., 1975, Relative contributions of sediment from source areas and transport processes. *Present and Prospective Technology for Predicting Sediment Yields and Sources*, Proceedings of the Sediment-Yield Workshop, USDA Sedimentation Laboratory, Oxford, Mississippi, November 28-30, 1972, United States Department of Agriculture, ARS-S-40: 66-73.

Argabright, M. S., Cronshey, R. G., Helms, J. D., Pavelis, G.A., and Sinclair, H. R. Jr., 1996, *Historical Changes in Soil Erosion, 1930-1992: The Northern Mississippi Valley Loess Hills*, Washington, U.S. Department of Agriculture, Natural Resources Conservation Service, Historical Notes Number 5, 92p.

Baker, J. P., 1990, An analysis of the surface hydrology in the Galena watershed: 1940-1987, M.S. Thesis, Department of Geography, University of Wisconsin, Madison, 99p.

Beach, T, 1994, The fate of eroded soil: sediment sinks and sediment budgets of agrarian landscapes in southern Minnesota, 1851-1988. *Annals of the Association of American Geographers*, Vol. 84 No. 1: 5-28.

Beckert, C., U.S. Army Corps of Engineers, Rock Island District, 1999 Interview by author, 11 February, hand written notes, Rock Island, Illinois.

Bhowmik, N. G., 1996, Impacts of 1993 floods on the Upper Mississippi and Missouri river basins in the U.S.A. *Water International*, Vol. 21: 158-169.

Brune, G.M., 1951, Sediment records in Midwestern United States, *International Association of Scientific Hydrology*, Tome III, Brussels Symposium: 29-38.

Bondurant, D.C., 1975, Chapter V, section E, sediment discharge quantities in Vanoni, V.A. (Ed.), *Sedimentation Engineering*, American Society of Civil Engineers, Manuals and Reports on Engineering Practice – No. 54: 588-589.

Butzer, K. W., 1974, Accelerated soil erosion: a problem of man-land relationships in Manners, Ian R. and Mikesell, Marvin W. (Eds.), *Perspective on Environment*, Association of American Geographers Commission on College Geography 13: 57-78.

Dimissie, M. M., 1996, Sediment load during flood events for Illinois streams, *Water International*, Vol. 21: 131-137.

Great River Environmental Action Team, 1980, *Channel Maintenance Handbook, (Supplement to the Great II Main Report)*, Upper Mississippi River.

Jordan, P.R., 1965, *Fluvial Sediment of the Mississippi River at St Louis, Missouri*, U.S. Geological Survey Water Supply Paper 1802, 89 p.

Karl, T. R., 1985, Perspective on climate change in North America during the Twentieth century. *Physical Geography*, Vol. 6 No.3: 207-229.

Knox, J. C., Bartlein, P.J., Hirschboeck, K.K., Muckenhirn, R.J., 1975, *The Response of Floods and Sediment Yields to Climatic Variation and Land Use in the Upper Mississippi Valley*, IES Report 52, University of Wisconsin-Madison, 76 p.

Knox, J. C., 1977, Human impacts on Wisconsin stream channels. *Annals of the Association of American Geographers*, Vol. 67: 323-342.

Knox, J. C., Cary, S.J., Magilligan, F.J., 1981, *Climate Variation and the Mobility and Storage of Sediment in Watersheds*, University of Wisconsin, Madison, Water Resources Center Technical Report 81-03, 56p.

Knox, J. C., 1987, Historical valley floor sedimentation in the upper Mississippi Valley. *Annals of the Association of American Geographers* 77: 224-244.

Knox, J. C., 1998, Long-term episodic changes in magnitudes and frequencies of floods in the Upper Mississippi River Valley, in Brown A.G. and Quine, T. A. (Eds.), *Fluvial Processes and Environmental Change*, John Wiley and Sons Ltd., London: 255-282.

Knox, J. C., 1997, Agriculture, erosion, and sediment yields, in Orme, A. (Ed.), *Physical Geography of North America*, in press.

Kuhnle, R. A., Binger, R. L., Foster, G. R. and Grissinger, E. H., 1996, Effect of land use changes on sediment transport in Goodwin Creek. *Water Resources Research*, Vol. 32 No. 10: 3189-3196.

Mack, F. J., 1970, Sediment yields in the Upper Mississippi River Basin, *Proceedings of a Seminar on Sediment Transport in Rivers and Reservoirs 7-9 April 1970*. The Hydrologic Engineering Center, Corps of Engineers, U.S. Army.

McHenry, J.R., Ritchie, J.C., Cooper, C.M., and Verdon, J., 1984, Recent rates of sedimentation in the Mississippi River, in Weiner, J.G., Anderson, R.V., McConville, D.R., (Eds.), *Contaminants in the Upper Mississippi River* (Proceedings of the 15th Annual Meeting of the Mississippi River Research Consortium). Butterworth Publishers, Boston: 99-117.

Meade, R. H., 1982, Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. *The Journal of Geology*. Vol. 90, No. 3: 235-253.

Meade, R. H. (Ed.), 1995, *Contaminants of the Upper Mississippi River, 1987-1992*, U.S. Geological Survey Circular 1133, U.S. Government Printing Office: Denver, Colorado, 140 p.

Miller, S.A., Ritter, D.F., Kochel, R.C., Miller, J.B., 1993, Fluvial responses to land-use changes and climatic variations within the Drury Creek watershed, southern, Illinois. *Geomorphology*, Vol. 6: 309-329.

Nielson, D. N., Rada, R. G. and Smart, M. M., 1984, Sediments of the Upper Mississippi River: their sources, distribution, and characteristics, in Weiner, J.G., Anderson, R.V., McConville, D.R., (Eds.), *Contaminants in the Upper Mississippi River* (Proceedings of the 15th Annual Meeting of the Mississippi River Research Consortium). Butterworth Publishers, Boston: 67-98.

Piest, R.F. and Miller, C.R., 1975, Chapter IV, sediment sources and sediment yields in Vanoni, V.A. (Ed.), *Sedimentation Engineering*, American Society of Civil Engineers, Manuals and Reports on Engineering Practice – No. 54: 437-493.

Piest, R.F., Bradford, J.M., and Spomer, R.G., 1975, Mechanisms of erosion and sediment movement from gullies. *Present and Prospective Technology for Predicting Sediment Yields and Sources*. Proceedings of the Sediment-Yield Workshop, USDA Sedimentation Laboratory, Oxford, Mississippi, November 28-30, 1972, United States Department of Agriculture, ARS-S-40: 162-176.

Richards, K., 1993, Sediment delivery and the drainage network, in Beven, K. and Kirkby, M.J. (Eds.), *Channel Network Hydrology*, John Wiley & Sons, Ltd.: 221-253.

State Soil and Water Conservation Committee, 1963, *A Brief History of Soil Erosion Control in Wisconsin*, University of Wisconsin Extension Service: Madison, Wisconsin. 48p.

Sullivan, C. H., 1970, The Kansas City District suspended sediment load computer program. *Proceedings of a Seminar on Sediment Transport in Rivers and Reservoirs 7-9 April 1970*. The Hydrologic Engineering Center, Corps of Engineers, U.S. Army.

Trimble, S. W. and Lund, S. W., 1982, Soil conservation and the reduction of erosion and sedimentation in the Coon Creek basin, Wisconsin. U.S. Geological Survey Professional Paper 1234: 1-35.

United States Army Corps of Engineers, 1989, Sedimentation Investigations of Rivers and Reservoirs, Chapter 3, Engineer Manual EM 1110-2-4000, 1-27.

United States Department of Commerce, *Climatological Data of Iowa, 1968-1996*, National Climatic Data Center, Asheville, NC.

United States Department of Commerce, *Climatological Data of Minnesota, 1968-1996*, National Climatic Data Center, Asheville, NC.

United States Department of Commerce, *Climatological Data of Wisconsin, 1968-1996*, National Climatic Data Center, Asheville, NC.

Upper Mississippi River Comprehensive Basin Study, 1970, Fluvial sediment, Annex G, U. S. Army Engineer District, Rock Island.

Wisconsin Agriculture Reporting Service, 1978, *Snow and Frost in Wisconsin, 1961-1977*, United States Department of Agriculture Economics, Statistics, & Cooperative Service: Madison, WI. 38p.

APPENDICES

Appendix A. East Dubuque Record: Percentage of Data Available.

Water Year	# Days Measured	% Days Measured	# Spring-Summer Days	% Spring-Summer Days	Water Year	# Days Measured	% of Days Measured	# Spring-Summer Days	% Spring-Summer Days
1943	122	33.4%	122	66.3%	1970	306	83.8%	184	100.0%
1944	122	33.3%	122	66.3%	1971	300	82.2%	179	97.3%
1945	106	29.0%	106	57.6%	1972	337	92.1%	182	98.9%
1946	145	39.7%	133	72.3%	1973	330	90.4%	182	98.9%
1947	116	31.8%	104	56.5%	1974	295	80.8%	176	95.7%
1948	66	18.0%	66	35.9%	1975	278	76.2%	158	85.9%
1949	200	54.8%	170	92.4%	1976	280	76.5%	156	84.8%
1950	248	67.9%	157	85.3%	1977	270	74.0%	183	99.5%
1951	244	66.8%	153	83.2%	1978	242	66.3%	153	83.2%
1952	214	58.5%	153	83.2%	1979	268	73.4%	168	91.3%
1953	245	67.1%	184	100.0%	1980	264	72.1%	155	84.2%
1954	275	75.3%	184	100.0%	1981	253	69.3%	160	87.0%
1955	275	75.3%	184	100.0%	1982	197	54.0%	126	68.5%
1956	275	75.1%	184	100.0%	1983	287	78.6%	170	92.4%
1957	245	67.1%	184	100.0%	1984	234	63.9%	153	83.2%
1958	261	71.5%	170	92.4%	1985	258	70.7%	167	90.8%
1959	244	66.8%	153	83.2%	1986	270	74.0%	176	95.7%
1960	214	58.5%	153	83.2%	1987	271	74.2%	158	85.9%
1961	263	72.1%	172	93.5%	1988	280	76.5%	177	96.2%
1962	244	66.8%	153	83.2%	1989	316	86.6%	172	93.5%
1963	244	66.8%	153	83.2%	1990	308	84.4%	184	100.0%
1964	244	66.7%	184	100.0%	1991	307	84.1%	182	98.9%
1965	183	50.1%	123	66.8%	1992	272	74.3%	182	98.9%
1966	275	75.3%	184	100.0%	1993	238	65.2%	162	88.0%
1967	0	0.0%	0	0.0%	1994	252	69.0%	143	77.7%
1968	234	63.9%	152	82.6%	1995	251	68.8%	181	98.4%
1969	246	67.4%	165	89.7%	1996	265	72.4%	174	94.6%

Approved By _____   _____

James C. Knox, Professor, Dept. of Geography   Date